there in the summer in any year. True, the seasonal succession is not altogether clarified thereby, because of the certainty that annual differences are sometimes wider than the seasonal differences; 1916 may have been a fresh autumn, while the summers of 1913 and 1915 were certainly more saline than those of 1912 or 1914. At least there is nothing in this record to suggest an active inward pulse of slope water during the early autumn, but rather the reverse; and the relationship between the salinities for that date, on the one hand, and the curves for July 17, 1912, and August 22, 1914, on the other (stations 10007 and 10254), is what might be expected in the normal seasonal succession, with vertical stirring by tidal currents, winds, and waves becoming increasingly more effective through the autumn, when cooling at the surface decreases the vertical stability of the water.

We have no data for salinity on the offshore banks—Georges or Browns—for October or later in the autumn; but profiles of the continental shelf in the offing of Marthas Vineyard and a few miles farther west, run by the *Grampus* during the third week of October, 1915 (stations 10331 to 10334), and on November 10 and 11, 1916 (fig. 162), show that if slope water had worked in over this sector of the shelf along this line during the preceding summers it had moved out again from the edge of the continent by mid autumn, leaving values lower than 34 per mille out to the 120-meter contour. It is likely, therefore, that such encroachments of high salinity over the outer edge of the continental shelf off southern New England as are described above (p. 796) are strictly summer events. For water as saline as 34 per mille to continue on this part of the shelf after the end of September would, it seems, be an unusual event.

If the inshore ends of these two profiles, in combination, represent the usual October-November state, and if conditions prevailing there in August, 1914 (p. 796, fig. 158), are equally representative of that season, the coastwise water less saline than 32.5 per mille spreads out from the land, seaward, during the autumn, until the isohaline for this value includes the bottom out to the 40 to 60 meter contour and the surface halfway acoss the shelf.[5] The relationship between this November profile and the profile off New York for that August affords further evidence of similar import, as remarked elsewhere (Bigelow, 1922, p. 125, figs. 23 and 38).

The most interesting alteration that takes place later in the autumn is that the vertical range of salinity in the upper 100 meters, like that of temperature, decreases as the water loses stability and as tides and winds stir it more and more actively.

Observations on the salinity of the gulf for the last half of November and first half of December have been confined to the bowl at the mouth of Massachusetts Bay off Gloucester in 1912 (Bigelow, 1914a, p. 416), and to the deep trough of the Bay of Fundy, between Grand Manan and Nova Scotia, in 1916 and 1917 (Mavor, 1923, p. 375).

At the first of these localities and years salinity had become virtually homogeneous at about 32.5 per mille from the surface down to a depth of about 50 meters by November 20, increasing slightly with increasing depth to 32.66 per mille at bottom in 62 meters (fig. 111). However, the fact that virtually no alteration of salinity had taken place at the bottom there since the preceding August (stations 10045

[5] On the August profile (fig. 158) water less saline than 32.5 per mille did not touch the bottom at all at depths greater than 20 meters.

and 10046), though that of the surface had increased from 31.67 to 31.92 per mille to 32.57 per mille during the interval, is proof that the autumnal progression also reflected an indraft of more saline water over the rim.

Some salting of the whole column of water is to be expected, therefore, at the mouth of Massachusetts Bay during the late autum, besides the increase at the surface that stirring by tidal currents would, of itself, effect at this season. Although this alteration was not continuous in 1912, when salinity was almost precisely the same on December 4 as it had been on November 20 at the station in question,[6] it

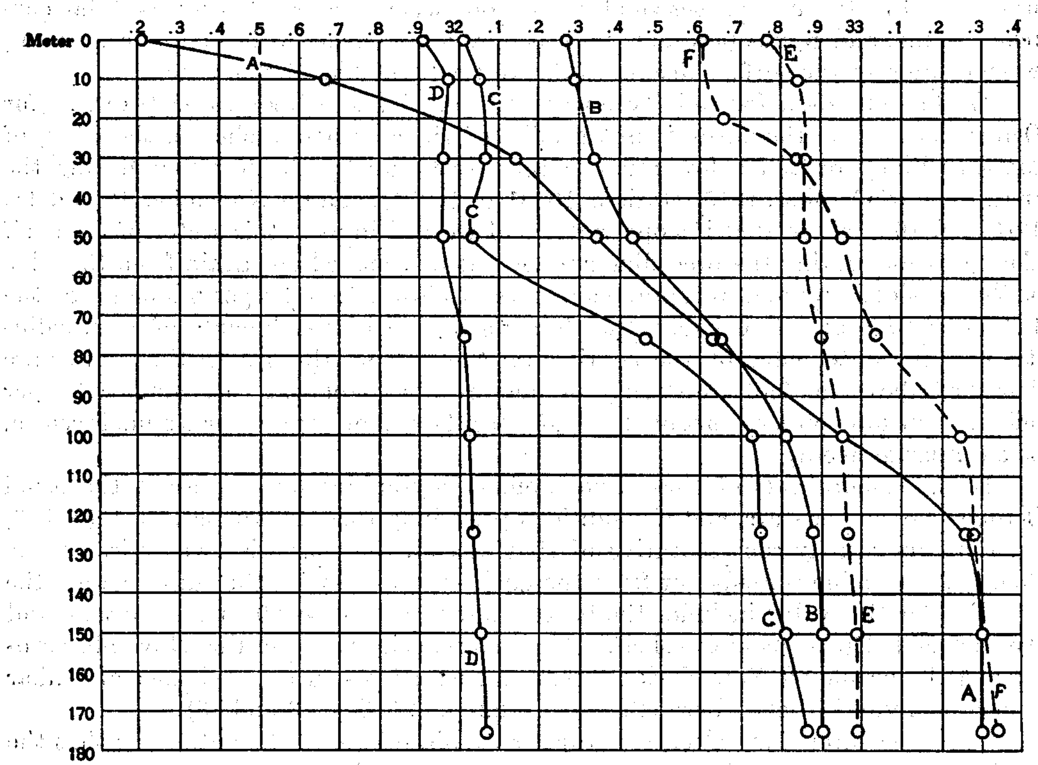

FIG. 161.—Vertical distribution of salinity in the Bay of Fundy between Grand Manan and Nova Scotia, in various months, from Mavor's table (Mavor, 1923, p. 375, *Prince* station 3). A, July 31, 1917; B, October 2, 1917; C, December 5, 1917; D, January 19, 1918; E, December 2, 1916; F, January 3, 1917

raised the salinity of the entire column (now homogeneous, surface to bottom) to about 32.75 per mille by the 23d of that month.

Mavor (1923) also records a considerable increase in the salinity of the upper strata of the Bay of Fundy from October 4, 1916, through November, although the bottom water continued virtually unchanged throughout that autumn. The vertical distribution for October 4 of that year[7] is especially interesting, the salinity being highest at 50 meters, with less saline water below it as well as above, and with a very abrupt increase near the bottom. A distribution of this sort, decidedly unusual

[6] 32.56 per mille at the surface and at 46 meters; 32.61 per mille near bottom in 70 meters depth.

[7] 10 meters, 31.9 per mille; 50 meters, 32.6 per mille; 75 meters, 32.4 mille; 150 meters, 32.5 per mille; and 175 meters, 33 per mille.

in the Gulf of Maine region, suggests indrafts from the basin offshore at two levels— one centering at about 50 meters and the other over the bottom.

In 1917 the autumnal progression of salinity in the Bay of Fundy was of the reverse order (fig. 161), Mavor's (1923) records showing a decrease of about 1.2 per mille at all depths from October to December, as follows:[8]

Depth, meters	Oct. 2	Dec. 5	Depth, meters	Oct. 2	Dec. 5
Surface	32.27	32.00	100	32.81	32.72
50	32.43	32.03	175	32.90	32.86

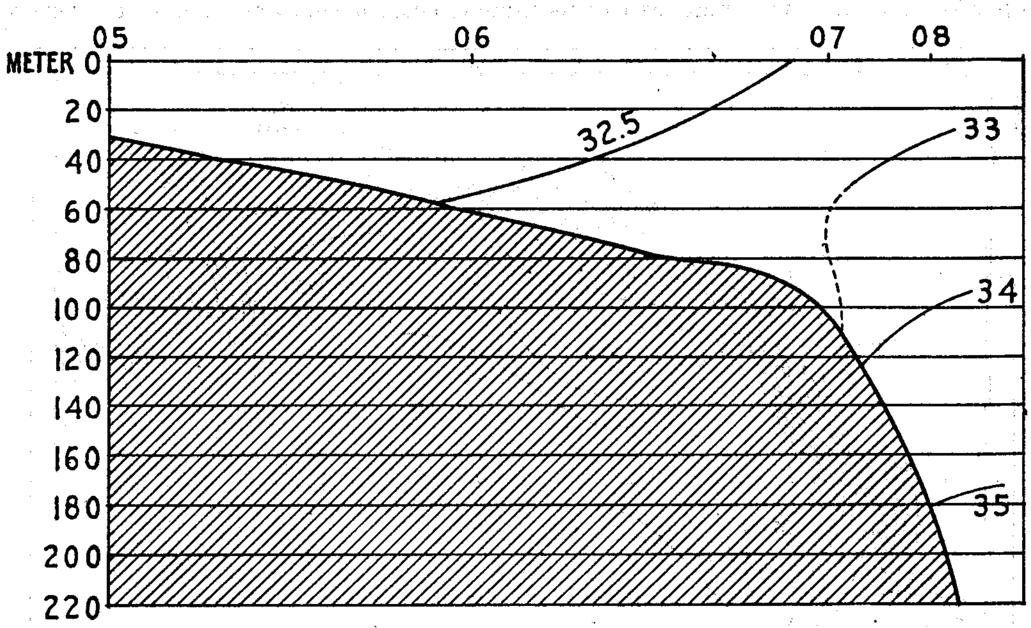

FIG. 162.—Salinity profile crossing the continental shelf off Marthas Vineyard, November 10 and 11, 1916. (From Bigelow, 1922, fig. 38)

It is obvious that with salinity increasing in the one year of record, decreasing in the next, neither an increase nor a decrease can be named as normal for the Bay of Fundy in late autumn. Freshening is probably to be expected there in years when the autumnal rains are heavy and the discharges from the St. John and from the other rivers tributary to the bay are correspondingly great, especially if the indraft over the bottom (which varies from year to year) is less active than usual. On the other hand, salting will follow after summers and autumns with light rainfall or with more than the usual contribution of saline bottom water. This explanation is partly corrobated by the fact that the year's precipation showed a deficiency of 11.45 inches from the mean at Eastport in 1916 (when the salinity of the bay rose in autumn), with every month from August to November falling low.

[8] Condensed from Mavor (1923, p. 375).

SALINITY IN MIDWINTER

The general oceanographic survey of the inner part of the gulf carried out by the *Halcyon* during the last days of December and first half of January, 1920–21, affords our only picture of the salinity of the offshore waters for that season.

These midwinter observations prove interesting from several view points. In the first place, when added to the winter records for Massachusetts Bay and for the Bay of Fundy for other years they show that little alteration takes place in salinity from autumn to midwinter, evidence that this season sees no extensive indraft of the saline slope water over the bottom. The regional distribution of salinity in the upper 100 meters gives evidence to this same effect, for this was highest near shore

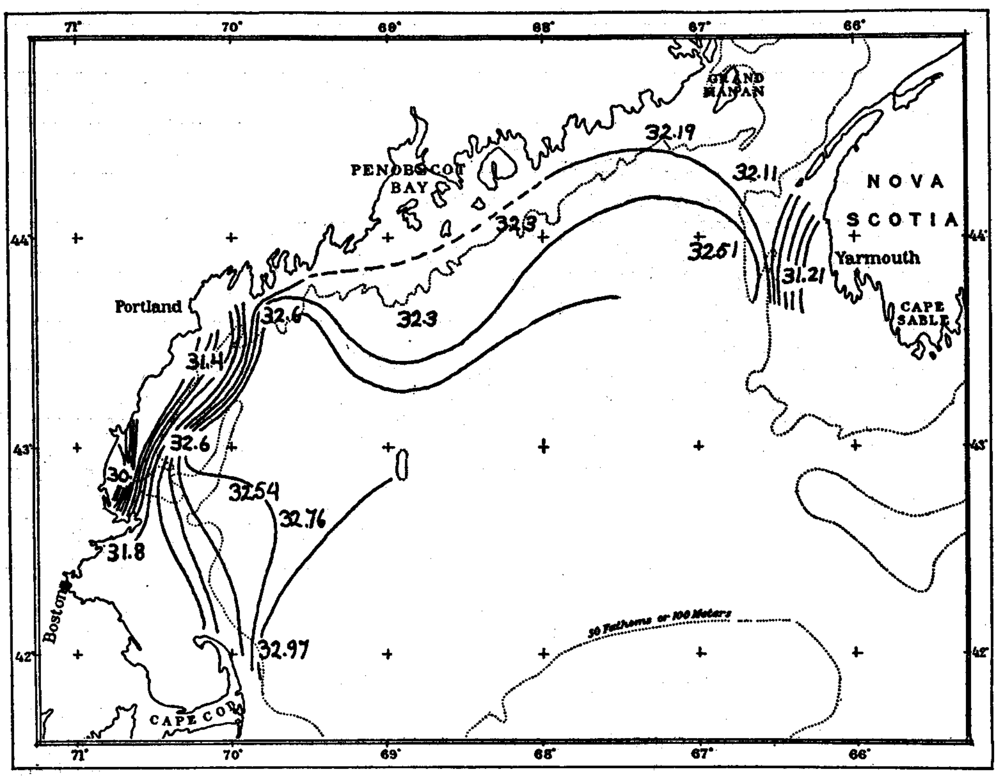

FIG. 163.—Salinity at the surface, December 29 1920, to January 9, 1921. Contours for every 0.2 per mille

in the western side of the gulf as in May instead of in the eastern, as is the rule at other times of year. This distribution appears most clearly on the surface projection (fig. 163), with 32.7 per mille off Cape Ann but only 32.5 per mille in the Nova Scotian side of the basin; likewise at 40 meters and at 100 meters, where these same localities were the most saline. These, in fact, were the only stations where the 100-meter salinity was then higher than 33 per mille, so that this isohaline paralleled the northern and western slopes of the gulf at this level.

The bottom water of the two sides of the basin at 200 meters and deeper then proved almost precisely alike in the two sides of the basin (about 33.9 per mille off

Cape Ann, stations 10490 and 10503, fig. 164, and 33.93 per mille in the northeastern side). However, the submarine rim of the Bay of Fundy, in the one side of the gulf, and the partial inclosure of the trough west of Jeffreys Ledge, in the other, hinder free exchange of bottom water in midwinter as effectively as they do in summer (p. 776), for the salinity was only 32.87 per mille at 150 meters to the west of Jeffreys Ledge, contrasting with 33.75 per mille in the open basin to the east of it. The

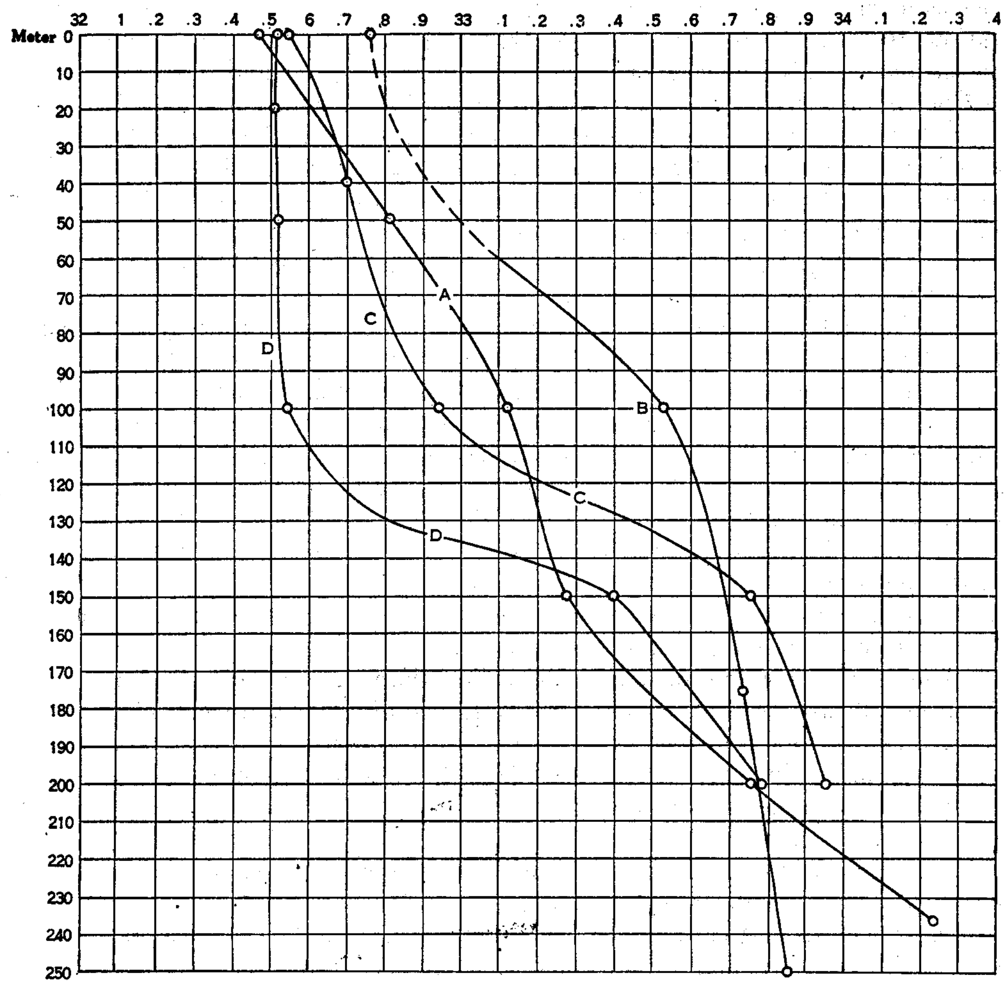

FIG. 164.—Vertical distribution of salinity in the western side of the basin in the offing of Cape Ann. A, August 31, 1915 (station 10307); B, December 29, 1920 (station 10490); C, January 9, 1921 (station 10503) D, February 23, 1920 (station 20049)

difference was nearly as great between the Bay of Fundy and the open gulf, off its mouth, at this same level (32.75 per mille at station 10499; 33.37 per mille at station 10502).

We have found this same general rule applying equally to the deep bowl off Gloucester at all other seasons; but on December 29, 1920, the deep strata were much more saline there (station 10489) than were corresponding levels in the open basins, whether off Cape Ann (station 10490) or off Cape Cod (station 10491); more saline, too, than at a neighboring location at any time during the winter of 1912–13. If these determinations were correct,[9] they mean that bottom water had been welling up into the bowl from greater depths in the basin at some time shortly previous. However, this movement had then ceased, and the inequalities in salinity were decreasing; otherwise the temperature would have been about the same at the surface as in the deeper layers (6.9° to 7°), instead of more than 1° lower (5.56° at station 10489). It is certain, also, that the unexpectedly high salinity did not persist long at this locality, for the whole column of water had freshened to 32.6 to 32.7 per mille there by the 5th of the following March (station 10511).[10]

Nor did any upwelling that may have taken place off the mouth of Massachusetts Bay in December, 1920, involve the inner parts, for the whole column of water proved decidedly less saline off Boston Harbor on the 29th (station 10488) than at the mouth of the bay (station 10489); less saline, too, than near Gloucester on January 30, 1913 (station 10051), when salinity ranged from 32.56 per mille at the surface to 32.8 per mille on bottom.

During this midwinter the salinity of the superficial stratum of water was lowest (31 to 32 per mille) along the shore between Cape Ann and Cape Elizabeth, on one side of the gulf, and next the west coast of Nova Scotia, on the other, with a minimum of 30.02 per mille a few miles south of the mouth of the Merrimac River, no doubt reflecting the freshening effect of the latter, but slightly higher along the northern shore of the gulf (32.3 to 32.6 per mille) and in Massachusetts Bay (32.1 to 32.5 per mille). This regional distribution was paralleled at 40 meters (though with actual values averaging about 0.3 per mille higher), except that the minimum for this level was close to the Nova Scotian coast (31.3 per mille) instead of off the Merrimac River, proving the freshening effect of the latter to have been confined to the uppermost stratum of water at the time.

The narrow confines of water less saline than 32 per mille in midwinter, and the rather abrupt transition in the western side of the gulf to considerably higher values a few miles out at sea, contrasted with the much more extensive area inclosed by that isohaline in April and in May (figs. 101 and 120), reflect the fact that the rivers discharge much less water into the gulf in late autumn and early winter than they do in spring.

During the winter of 1912–13 the vertical stratification of the water at the mouth of Massachusetts Bay, characteristic of the summer season, gave place to a close approach to vertical homogeneity in salinity, as well as in temperature, by the middle of December, and so continued through the winter. Closer in to the shore, however, on both sides of Cape Ann, a greater vertical range of salinity persists into January and probably right through until spring.[11] In 1920–21 all the stations showed a vertical range of more than 0.3 per mille salinity in the upper 100 meters, except off Yarmouth, Nova Scotia, and off Cape Cod (stations 10501 and 10491), where the water was virtually homogeneous, surface to bottom, and near Seguin

[9] There is no technical reason to doubt their accuracy.

[10] In 1913 the salinity at a near-by locality continued to increase until Mar. 19, when it attained its maximum of 33 per mille at the surface and 33.17 per mille on bottom at a depth of 88 meters.

[11] Vertical range of 0.3 to 0.7 per mille in depths of 30 to 35 meters at stations 10051 and 10052 on Jan. 30, 1913.

Island (station 10495), where the salinity increased only from 32.6 per mille at the surface to 32.77 per mille at 75 meters.

Local freshening of the surface, just described (p. 806), was then responsible for the very considerable vertical range of 2.6 per mille in water only 30 meters deep between Cape Ann and the Merrimac River, with differences of 0.8 to 1.4 per mille between the surface and the 75 to 100 meter level off Cape Elizabeth and off Cape Ann (stations 10488, 10489, 10492, and 10494).

It is certain, however, that as the surface continued to cool during that winter the decrease in vertical stability was accompanied by a progressive equalization of salinity in the upper 100 meters; for the surface and the 100-meter level differed by less than 0.2 per mille in salinity at five out of seven of the stations for the following March (stations 10505 to 10511). Thus, the seasonal cycle was fundamentally the same in this respect in 1920–21 as in 1912–13, except that it was more tardy in its early progression.

No general survey of the salinity of the gulf has yet been attempted during the last half of January or the first half of February—on the whole the coldest season (p. 655). However, periodic observations taken in Massachusetts Bay during this period of 1913, hydrometer readings taken at 15 stations by the *Fish Hawk* in its southern side on February 6 and 7, 1925, and Mavor's (1923) winter records for the Bay of Fundy in 1916 and 1917 show that no very wide change is to be expected in the salinity of the gulf during the last half of the winter.

These *Fish Hawk* determinations ranged from about 32.3 per mille to about 33.3 per mille, according to the precise locality, averaging lowest in the hook of Cape Cod, where the surface was about 32.3 to 32.4 per mille, and highest in the center of the bay (whole column close to 33 per mille, surface to bottom). The maximum difference in salinity between surface and bottom was then only 0.4 per mille (average difference about 0.2 per mille), with the water virtually homogeneous, surface to bottom, at the two deepest stations (about 70 meters deep).

It is interesting to find the salinity of the deeper part of the bay for February 7, 1925, almost exactly reproducing the values recorded off Gloucester on the 13th of the month in 1913 (station 10053, surface 32.83 per mille, bottom 32.84 per mille); evidently neither of these winters, as contrasted with the other, can be described as "fresh" or "salt" in the bay. In both 1913 and 1925 the water away from the immediate influence of the shore line was equally homogeneous in salinity from top to bottom by these dates; but the data for the two years combined bring out a decided regional difference in this respect, with the surface continuing 0.3 to 0.4 per mille less saline than the deeper strata along the northern and southern margins of the bay, no doubt because of land drainage.

Although we have made no offshore stations in the gulf between the middle of January and the last week of February, some knowledge of the ebb and flow of the slope water over that period is obtainable from the seasonal progression from February to March in the deeper parts of Massachusetts Bay, and from the salinity of the basin off Cape Ann for March 5, 1921 (station 10510), compared with the preceding December and January (stations 10490 and 10503).

In 1913 the salinity rose to about 32.8 per mille at the surface, to 32.9 per mille on bottom in 70 meters, at the mouth of the bay by January 16—a mean increase of about 0.2 per mille for the preceding six weeks. Apparently this indraft of saline water from offshore then slackened, for on February 13 the water (then virtually homogeneous, top to bottom) still had this same salinity. It then salted once more to 33.04 per mille on the bottom by March 4 (no change at the surface), with a slight further increase during the next two weeks to 33 per mille at the surface and 33.17 per mille on bottom, which proved the maximum for the year, succeeded by the vernal freshening already described (p. 723).

In 1925 the salinity of the deep central part of the bay remained virtually unchanged from February 7[12] until March 10, at about 33 per mille, surface to bottom.

In 1921 the bottom of the basin off Cape Ann showed no appreciable alteration in salinity from December and January to March, with bottom readings of 33.87 to 33.99 per mille at all three of these stations (10493, 10503, and 10510) in depths of 200 to 250 meters; but the bottom water of the bowl at the mouth of Massachusetts Bay off Gloucester freshened by about 1 per mille (stations 10489 and 10511, 33.84 and 32.7 per mille).

It is doubtful, therefore, whether any appreciable drift inward over the bottom of the gulf took place during the winters of 1921 or 1925; and while rising salinity gave evidence of some such movement into Massachusetts Bay in the winter of 1913, the alteration from month to month was so small as to prove it small in volume as well as intermittent in character. In the Bay of Fundy, again, according to Mavor (1923, p. 375), salinity decreased slightly between January 3 and February 28 in 1917.[13] In short, such evidence as is available suggests that the winter sees a decided slackening of the drift of slope water inward through the Eastern Channel.

SUMMARIES OF SALINITY FOR REPRESENTATIVE LOCALITIES

Summaries of the annual cycle follow for localities where the greatest number of observations have been taken. Unfortunately, none of these stations in the open gulf afford a complete year's cycle at intervals close enough, either in time or in depth, to be more than preliminary, but at the least they will serve to illustrate the major changes to be expected from season to season and from the surface downward.

BAY OF FUNDY

Mavor's (1923) records of salinity on 18 occasions, covering the interval from August 25, 1916, to May 10, 1918, at a station near the mouth of the Bay of Fundy, between Grand Manan and Nova Scotia, are especially instructive in this connection. The outstanding event in the annual cycle of salinity here is the sudden freshening of the surface that takes place in spring (fig. 165), occasioned by the outpouring of fresh water from the rivers emptying into the bay—chiefly from the St. John. This occurred between the 10th of April and the 10th of May in both of these years (probably the usual date). As described above (p. 743), the surface then salts again as the thin stratum so affected mixes with the salter water from below,

[12] No salinities were recorded prior to that date during that winter.

[13] *Prince* station 3, Jan. 3, salinity 32.6 per mille at the surface, 33.24 per mille at 100 meters, and 33.33 per mille at 175 meters, while on Feb. 28 the values at these same depths were 32.66, 32.97, and 33.01 per mille.

to reach its maximum for the year in October (as in 1917) or November–December (as in 1916)—an annual difference no greater than might be expected in any coastal region where the precise salinity is so largely governed by the volume of river water.

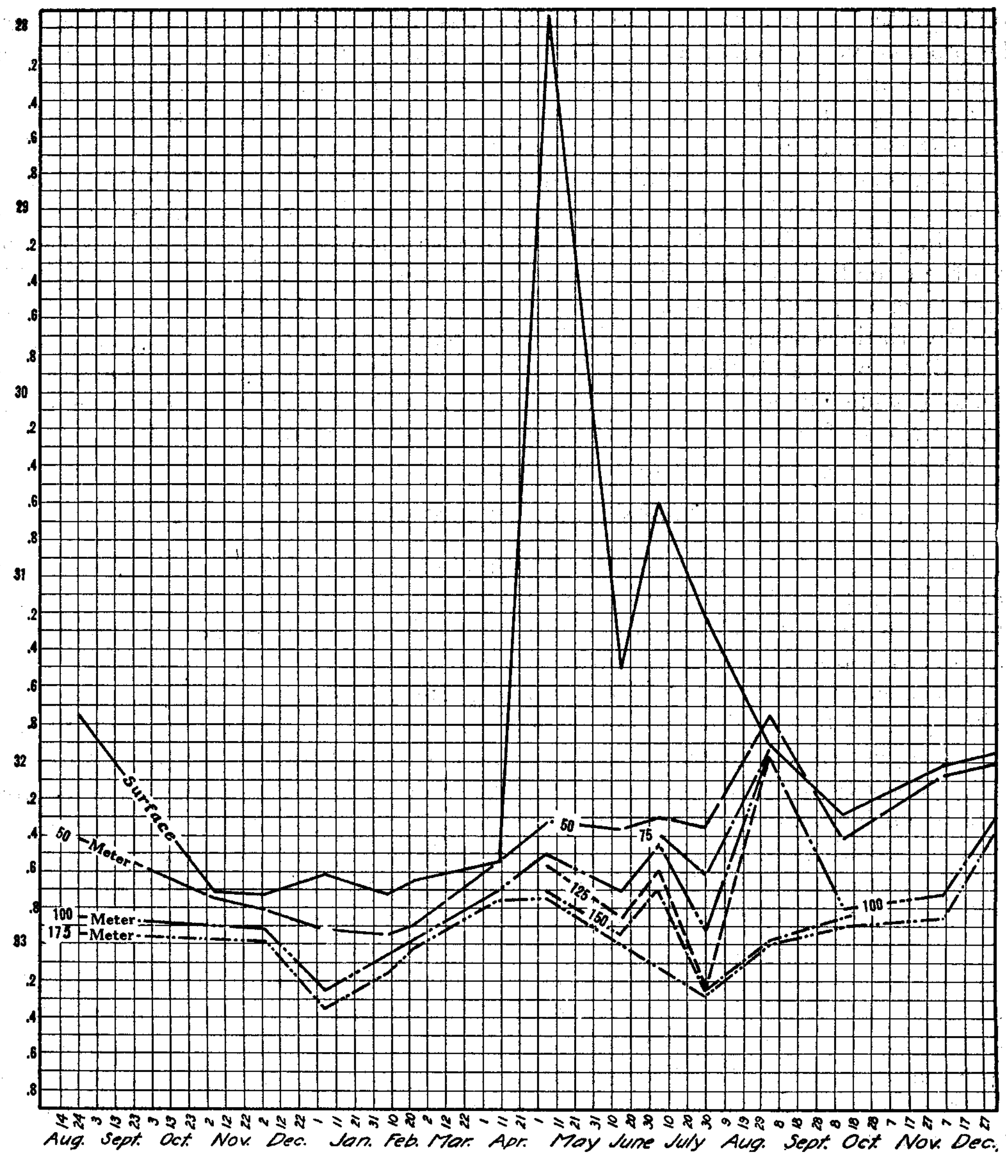

FIG. 165.—Seasonal variations of salinity in the Bay of Fundy, August, 1916, to December, 1917, at the surface, 50 meters, 100 meters, and 175 meters, constructed from Mavor's (1923) tables

During the remainder of the year the surface salinity of this part of the bay is comparatively uniform.

Vernal freshening is progressively less and less effective with increasing depth, so that the salinity of the 50-meter level decreased only by about 1.2 per mille from its maximum to its minimum during the year illustrated, the 100-meter level by about as much, though the surface freshened by upwards of 4 per mille. This secular change also culminates later in the season with depth, just as vernal warming does (p. 664), with the mid-stratum least saline about the first of September or four months after the salinity of the surface has passed its minimum for the year. The progressive freshening of the 75 to 100 meter stratum was also interrupted in the July in question by some temporary welling up of more saline water from below.

The graph (fig. 165) is also instructive for its demonstration that the incorporation of the vernal outpouring of river water into the superficial strata of the bay has little, if any, effect on the salinity at depths greater than about 140 to 150 meters. Consquently the periodic variations that take place in its deepest waters reflect corresponding variations in the volume and precise salinity of the inflow over its rim from the open basin of the gulf outside. Slight undulations in the curve for the 175-meter level (fig. 165) show a sort of irregular pulse in this respect, in which the annual variations seem (from available data) wider than the seasonal variations.

This graph is a striking illustration of the general rule that the vertical range of salinity is widest in coastwise boreal waters, generally, at the time of the vernal freshening of the surface; narrowest in autumn and winter, when little land water enters and when winds, waves, and tidal currents stir the water most actively.

MASSACHUSETTS BAY REGION

The regional distribution of salinity in and abreast of Massachusetts Bay is such that a difference of 3 to 5 miles in the location, nearer to or farther from shore, is associated with wide differences in salinity, especially at the surface, so closely does the freshest water hug the land during most of the year.

The accompanying composite graph (fig. 166), based on monthly averages for various years 8 to 12 miles of Gloucester, is offered as an approximation of the seasonal progression to be expected in years neither unusually salt nor unusually fresh, unusually late in seasonal schedule nor unusually early;[14] and it pretends to nothing more. It does not represent any one year; in fact, some of the individual readings have differed considerably from the smoothed curve laid down here, differences reflecting the annual variations described in the preceding pages.

The curve for the surface corroborates an earlier graph, based on less extensive data (Bigelow, 1917, p. 207, fig. 42), to the effect that the superficial stratum of water may show vernal freshening as early as the end of February or a month earlier than in the Bay of Fundy (p. 808); but additional records for the spring months have proven that the minimum salinity for the year is to be expected considerably earlier in the season in Massachusetts Bay than I formerly supposed, and that the salinity falls to a much lower value there at its annual minimum. It is a fortunate chance that our survey has included one spring (1920) that may be described as "fresh" in this region, and one (1925) as "salt." These two years differed little during the first half of April (p. 728; 32 to 32.4 per mille), and the surface seems to have freshened to its minimum about the last of April or first of May in both years.[15] However, while

[14] The station occupied at this general locality in July, 1916, is omitted, that being an unusually fresh year.

[15] Observations were not taken at intervals close enough to establish the date more closely than this.

this reduced the surface salinity by at least 3.2 per mille between April 9 and May 4 (29.1 per mille) in 1920, the lowest value recorded at the mouth of the bay in 1925 was 31.3 per mille on April 23 and again on May 22, though it is possible, of course, that the "peak" fell between these two dates, as already remarked (p. 741).

A considerably higher surface value at this locality on May 4, 1915 (station 10266, 32.3 per mille), is reconcilable on the assumption (discussed above) that the effects of vernal freshening were more closely confined to the immediate vicinity of the land in that spring. However, this record is averaged on the graph (fig. 166).

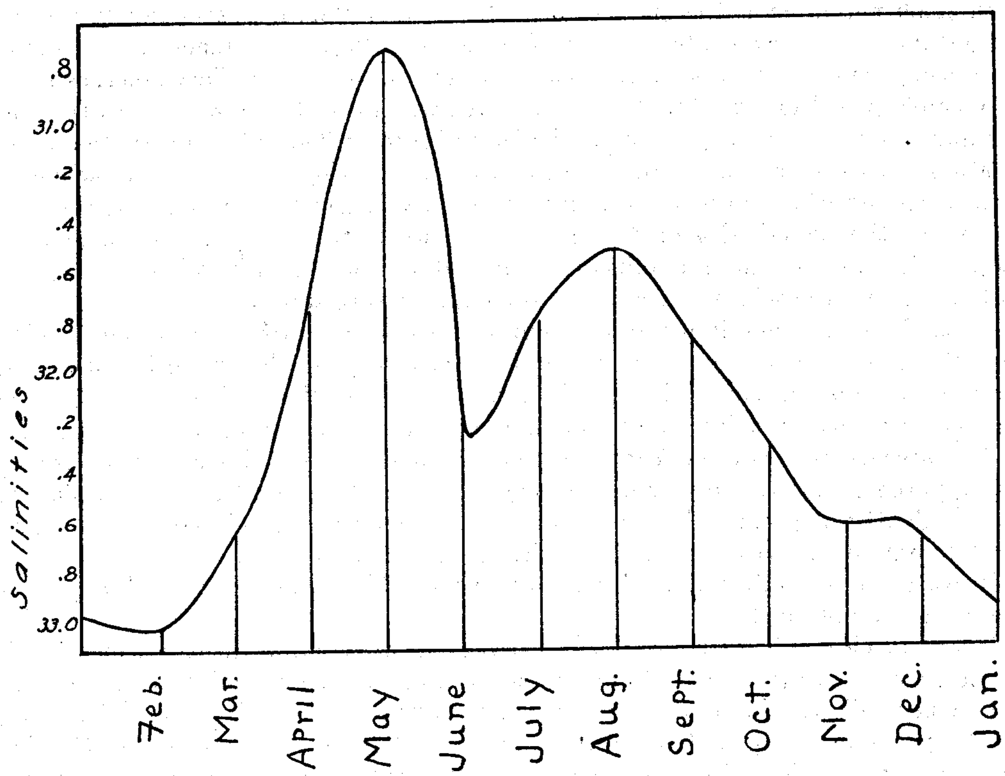

FIG. 166.—Seasonal progression of salinity at the surface at the mouth of Massachusetts Bay, 12 miles off Gloucester, based on monthly averages of the records in the various years. The data for July, 1916, are omitted for the reason given on p. 810

Taking one year with another, the lowest surface salinity of the year is to be expected at this general locality between the last week of April and last week of May. Surface values lower than 31 per mille (sometimes as low as 29 per mille) are to be expected there at some time during this period—a decrease of more than 2 per mille from the maximum salinity at the end of winter.

The vernal freshening at this particular region results chiefly from the discharges from the large rivers to the north (nearest of these is the Merrimac), for no large streams empty in the immediate vicinity. Consequently, any fluctuations in the volume and direction of the drift past Cape Ann will be mirrored by corresponding fluctuations in the salinity of the surface water at the mouth of Massachusetts Bay, and so may confuse the seasonal picture.

In 1925 the surface salinity remained close to the annual minimum at this locality for several weeks (perhaps this is always the case). A considerable increase was then recorded (to about 32.3 per mille; p. 756); but if this is an annual event (which is by no means certain) it is followed by a second freshening, for the surface records for this region for July and August, in the several years of record, have averaged only about 31.5 per mille (or 31.3 per mille, if one station for July, 1916, be included), with 32.09 per mille as the maximum. The salinity then increases slowly through the autumn and early winter, as just described (p. 799). Differences in circulation may bring the surface to its saltest there as early as the last of December, as seems to have happened in 1920 (p. 805), or not until well into March, as in 1913 (p. 808). Comparison between the graphs for the Bay of Fundy (fig. 165) and for the mouth of Massachusetts Bay (fig. 166) brings out the interesting difference that while the surface salinity of the former continues comparatively constant throughout the year, except for the period of 4 or 5 months that covers the vernal freshening and its eclipse, the salinity rises and falls over a period of 8 or 9 months off Massachusetts Bay, with only the winter describable as comparatively static.

The differences in salinity from season to season at the surface are so much wider than the differences at any given season from year to year that inclusion of the latter does not rob the composite graph (fig. 166) of its illustrative value. Annual fluctuations, however, introduce a more and more serious source of error at greater and greater depths, as the effects of vernal freshening from above become less and less apparent, until the former may nearly, if not quite, equal the seasonal fluctuations at depths no greater than 40 meters. Consequently, a combination of the data for different years gives a less trustworthy picture of the seasonal progression for the deep water; and monthly data for any one year, which would yield such a picture, are yet to be obtained.

Nevertheless, when such data as are available are combined, by seasons, for the 40-meter level[16] a rather definite progression does appear, with values averaging 32.8 to 33.1 per mille for the cold half of the year (November through March), decreasing to 32.6 per mille in April, 32.5 per mille in May, 32.3 per mille for July to October, and increasing again through the early winter. While the 40-meter value was as high there on June 16 and 17, 1925 (33.17 per mille), as any recorded for February or March, this is the only record for the period July to October that has been higher than the mean for the year (approximately 32.6 to 32.7 per mille). On the other hand, only 1 of the 10 records for the period January to March has fallen appreciably below the annual mean.

The salinity of the 40-meter level, therefore, may be expected to vary by about 0.7 per mille at the mouth of Massachusetts Bay during average years, being most saline at about the same season that the surface is at its maximum (late winter), but not at its freshest until two or three months after the salinity at the surface has passed its minimum (in May) and begun to increase once more. However, the unusually saline state of the water in this region in June, 1925, is sufficient evidence

[16] November to January, 6 stations; February to March, 5 stations; April to May, 4 stations; June, *Fish Hawk* cruise 14 in 1925; July to August, 6 stations; September to October, 2 stations for the several years.

that this progression may be interrupted by indrafts of water from offshore, or that the seasonal schedule may vary from year to year.

The 100-meter salinities for this locality have averaged about 32.9 to 33 per mille for the period February to July (extremes 33.8 and 32.5 per mille), with no definite seasonal variation during that period. All but one of the determinations for the period August to October have been appreciably lower (32.5 and 32.6 per mille) than any for the rest of the year, however. An average seasonal varition of about 0.3 per mille is thus indicated at 100 meters, reflecting the extreme depth to which vernal freshening from above is effective; but here, near its lower limit, this freshening does not culminate until a month or two later than at 40 meters, or four months later than at the surface.

The data collected so far fail to show whether any definite seasonal variation of this sort can be traced at depths greater than 100 meters at this locality.

Closer to land, in Massachusetts Bay off Boston Harbor, vernal freshening effects about as great a decrease in the salinity of the surface as at the mouth—from 32.1 to 32.2 per mille in March (of 1920 and 1921) to about 31 per mille in April and to about 30 per mille in May, followed by rather rapid recovery to 31 to 32 per mille through July and August. The lowest values have been recorded as early in the year at 40 meters as at the surface (about 31.6 to 31.7 per mille, April and May, 1920).

OFFING OF THE MERRIMAC RIVER

The truly remarkable extent to which the vernal discharges from the large rivers govern the seasonal cycle of salinity in the coastwise belt of the gulf is illustrated by the offing of the Merrimac. To the southward of the Isles of Shoals, in its train, vernal freshening is as sudden an event and the decrease in the salinity of the surface is as great (by about 4 per mille) as in the Bay of Fundy (p. 808); but in the trough between the Isles of Shoals and Jeffreys Ledge, only some 20 miles out from the mouth of the river, the extreme range of salinity so far recorded at the surface for the months of December, March, April, May, July, August, October, and November[17] has been only about 1.2 per mille (31.6 to 32.8 per mille); nor does vernal freshening seem to culminate there until August—three months later than along shore. Furthermore, its effect is so closely confined to the immediate surface here that it has little effect at 40 meters and is not definitely reflected at all in the records for 100 meters or deeper where the salinity has proved virtually constant from season to season and with but slight variations from year to year.

NEAR MOUNT DESERT ISLAND

The vernal freshening of the surface culminates at about the same season near Mount Desert Island as in the Bay of Fundy—i. e. late in April or early in May.[18] However, this sector of the coast is so much less affected by river water, and so much more open to the offshore waters of the gulf, that the seasonal range

[17] A total of 10 stations.

[18] Although only 12 sets of salinities have been taken here, the fact that we have records for 6 consecutive months for 1915, and that the other data are consistent with these, makes the graph a reliable picture of the cycle for the half year, May to October, which covers the season when the greatest changes in salinity take place.

of surface salinity is only about one-fourth as wide (about 1 per mille) as in the Bay of Fundy—half as wide as at the mouth of Massachussetts Bay. The surface off Mount Desert then salts again slowly right through the summer and early autumn, its salinity increasing from about 31.5 per mille on May 11, 1915 (station 10275), to to 32.66 per mille on October 9 (station 10328); and while we lack data for November and December it is probable that the surface is near its saltest here during the late autumn and early winter, for readings for January 1, 1921, and March 3, 1920, were somewhat lower and almost precisely alike (32.3 and 32.2 per mille).

The seasonal fluctuation associated with land drainage is strictly confined to the superficial stratum off this open coast, probably because the more saline water in the trough of the gulf tends to bank up along this part of the coastal slope here at all times of year. Thus the highest and the lowest salinities yet recorded at the 40-meter level near Mount Desert are only about 0.4 per mille apart (32.16 per mille, July 19, 1915, station 10302, and 32.6 per mille, August 13, 1913, station 10099). About the same range and the same maximum and minimum values were recorded near bottom at 80 meters, though the water at this depth proved most saline in January (station 10497, January 1, 1921, 32.6 per mille); least so in May (station 10274, May 10, 1915, 32.23 per mille).

GERMAN BANK

The seasonal cycle on German Bank appears from the following summary:

Date	Station	Salinity at the surface	Salinity at 40 meters	Date	Station	Salinity at the surface	Salinity at 40 meters
		Per mille	*Per mille*			*Per mille*	*Per mille*
Mar. 23, 1920	20085	[1]32.60	32.63	Aug. 14, 1912	10029, 10030	32.70	32.80
Apr. 15, 1920	20103	32.74	32.79	Aug. 12, 1913	10095	32.75	32.97
Apr. 28, 1919	[2]22	31.70	31.70	Aug. 12, 1914	10244	32.84	32.90±
May 7, 1915	10271	31.89	31.94	Sept. 2, 1915	10311	32.23	32.50
May 30, 1919	[2]38	31.67	31.70				
June 19, 1915	10290	32.07	32.10				

[1] Probably. [2] Ice Patrol station.

A seasonal variation of at least 1 per mille is thus to be expected there, with the whole column of water least saline sometime between the last of April and first of June, the exact date depending on the flow and ebb of the Nova Scotian current. Data for this part of the gulf during autumn and winter are desiderata.

WESTERN SIDE OF THE BASIN

The extent to which the salinity of the basin of the gulf is affected by the outrush of river water in spring depends more on the tracks of the latter than on the distance offshore. Consequently, the considerable variations that have been recorded in the salinity of the surface of the basin in the offing of Cape Ann from summer to summer no doubt reflect corresponding variations in the volume and direction of the drift from the north past Cape Ann.

In the summers of 1912 and 1914 this drift appears to have been turned sharply offshore by the jutting cape, so that the surface water of the neighboring parts of the basin was about 1 per mille less saline in July and August than the mean value to be expected there in spring. In 1915, however, the surface freshened by only about 0.5 per mille at that locality from May to June; and while salinity may have fallen somewhat lower that July (when no observations were taken), it was about the same there at the end of August (32.5 per mille at station 10307) as it had been in June.

The available data[19] show the surface freshest here in July or August, or three months later than at the mouth of Massachusetts Bay (p. 811), and not saltest until May (p. 745), when the coastwise belt is least saline, a seasonal difference associated with the geographic location.

It is not possible to follow the seasonal progression of salinity in the deeper strata of the basin from the data at hand because the annual variations outrange the seasonal variations even at as small a depth as 40 meters. I can only point out that the 40-meter salinity decreased from 33.15 per mille on May 5, in 1915, to 33 per mille on June 26 and to 32.75 per mille on August 31, suggesting that vernal freshening culminates later at this depth than at the surface, as, indeed, is to be expected. At 100 meters the values for May, June, and August, 1915, all fell close together (33.08 to 33.17 per mille); and the extreme range of variation so far recorded at this level, for all years and seasons, has only been from about 32.5 per mille to about 33.2 per mille in this part of the basin.

Pulses in the indraft of banks water govern the salinity of the deeps of the gulf (p. 848); and these are reflected in fluctuations from a minimum of about 33.5 per mille to a maximum of about 34.1 per mille at the 200-meter level in the basin off Cape Ann. However, as pointed out (p. 852), it is not yet known how regularly periodic these fluctuations are, and if periodic, their exact seasonal schedule.

ANNUAL SURVEY OF SALINITY ON THE BOTTOM

The salinity of the bottom water of the gulf (interesting chiefly for its biologic bearing) is determined in part by the depth and in part by proximity, on the one hand, to the Eastern Channel and on the other to the coastline, with the outflow from its rivers. It is also influenced by the Nova Scotian current and by the general anticlockwise eddy that occupies the basin of the gulf. In inclosed sinks and bowls the degree of isolation is the determining factor.

In summer and autumn the whole bottom of the open basin deeper than 175 meters has invariably proved salter than 33.5 per mille—salter than 34 per mille at most places and on most occasions. In 1914 a maximum of about 35 per mille was recorded for the southeastern part, out through the Eastern Channel (p. 785), but this may have been a somewhat higher value than is usual for that situation. The state of the gulf in the midwinter of 1920–1921 and in the spring of 1920, with the fact that all but two out of 31 records of the salinity of the two arms of the trough deeper that 175 meters have fallen between 33.8 and 34.5 per mille, irrespective of the time of year, make it unlikely that its bottom normally experiences a variation wider than about 0.5 per mille in salinity during the year, or from year to year, in depths greater than 150 meters. Animals living on bottom in deep water in the gulf

[19] Thirteen stations for the months of February, March, April, May, June, July, August, November, and December in various years.

therefore enjoy an environment that is virtually uniform in this respect from years end to years end. The only exception to this rule has been the eastward of Cashes Ledge, where we have found the salinity of the bottom water only 33.2 per mille in May at a depth of 185 meters (station 10269), contrasting with 33.6 to 34 per mille earlier in spring and in summer.

Certain other regional variations in the state of the bottom water of the trough also can be traced within more narrow limits. Thus, its eastern arm is usually slightly less saline along the western slope than the eastern, independent of depths. In the western arm, however, off Cape Ann, the salinity of the bottom water is more directly a factor of the depth. The salinity on the intervening broken bottom has usually been slightly below 34 per mille; once (in March, 1920) as low as 33.4 per mille. A month later, however, it had risen to 34.18 per mille at this same locality; and water of 34 per mille must overflow the irregular ridge south of Cashes Ledge with some regularity, this being its only route to the basin to the west. An overflow of this sort was, in fact, reflected by an increase in the bottom salinity there from 33.4 per mille on March 20, 1920, to 34.18 per mille on April 17 at depths of 175 to 200 meters (stations 20052 and 20114).

An unmistakable, if slight, increase in the bottom salinity, depth for depth, is characteristic of the floor of the gulf from the inner parts of its two troughs out to the entrance to the Eastern Channel, probably at all seasons.

We have found the bottom salinity of the depth zone between the 175 and 150 meter contours (narrow everywhere except north of Cashes Ledge) averaging about 33.6 per mille, winter and summer, ranging from occasional values close to 35 per mille (or even slightly higher) at the deeper level to a mean of about 33.3 per mille at the shoaler boundary. No definite seasonal variation is demonstrated in water as deep as this, but the recorded variations, station for station, are associated with the pulses in the inflowing bottom current (p. 690).

This depth zone is interesting, however, because it includes the isolated bowl at the mouth of the Massachusetts Bay, the trough west of Jeffreys Ledge, and the deeper parts of the Bay of Fundy, in all of which the bottom water is considerably less saline than at corresponding depths in the open basin outside. In the most nearly inclosed of the three—off Gloucester—the bottom water at any given time of year is virtually uniform from a depth of about 100 meters (slightly below the level of the inclosing rim) down to 170 meters.

Regional differences in salinity increase greatly at depths less than 150 meters as the water shoals, depending on the geographic location, with the changes of the seasons also governing the bottom salinity more and more, so that the picture becomes increasingly complex.

In the coastal zone between Cape Cod and Cape Sable the bottom salinity, at depths of 100 to 150 meters, has been found to vary from 32.38 per mille to 34.11 per mille, according to depth, locality, and date. On the whole it averages lowest in the bowl off Gloucester, in the trough west of Jeffreys Ledge, and in the Bay of Fundy (32.2 to 33.2 per mille for this depth zone); highest on the northeastern slope of the open basin near Lurcher Shoal, where we have had one bottom reading as high as 34.11 per mille in water only 120 meters deep (station 10245, August 12, 1914), with others of 33.4 to 33.8 per mille. The upper part of this depth zone also shows the seasonal effects of land drainage and of the Nova Scotian current. Thus, we have found the bottom of the Northern Channel freshening from about 33.6 per mille in March, 1920, to 32.8 per mille in April at 125 to 135 meters, with 32.9 per mille in July, 1914. Off Lurcher Shoal, where the bottom salinity has averaged about 33.7 per mille at the 100-meter contour in August and September, 33.5 per mille, March to April, and 33.08 per mille on January 4, 1921, it was only about 32.3 per mille at 90 meters on May 10, 1915 (fig. 108).

The bottom salinity of the northern and western sides of the gulf ranges from about 32.3 to 32.5 per mille along the 100-meter contour in August to 32.5 to 33 per mille in winter, according to the precise locality; and the 100 to 150 meter zone along the northern slopes of Georges Bank (here only a few miles wide) is close to 33 per mille in spring, summer, and at the end of the winter, with no definite seasonal variation demonstrable from the observations taken there so far.

On the seaward slope of Georges Bank these depths include the so-called "warm zone" (p. 530), the salinity of which has been sufficiently discussed in the preceding pages. I need only add here that it varies from about 34 per mille to upwards of 35 per mille, hence is considerably more saline than the corresponding depths anywhere within the gulf.

The zone included between the 40 and 100 meter contours is especially interesting because it comprises most of the important fishing grounds, both within the gulf, on Browns Bank, on all but the shoalest parts of Georges Bank, the South Channel, and the outer part of the continental shelf.

The bottom readings for July and August at stations so shoal have varied between 31.8 and 33.2 per mille around the western and northern slopes of the gulf, with 32 to 33.2 per mille on bottom in 40 to 140 meters at our June to August stations at the mouth of Massachusetts Bay.

Close in to the western shore of Nova Scotia, Vachon's (1918) record of 31.09 to 32.33 per mille at 40 to 45 meters off Yarmouth show the bottom averaging somewhat less saline, depth for depth, than in most other parts of the gulf. Bottom salinities are also low off Cape Sable (32 to 32.3 per mille in 50 to 55 meters in July and August, 1914). In the open Bay of Fundy, Mavor (1923) had 31.9 to 32.9 per mille in depths of 50 to 100 meters in August, 1919, while Vachon (1918) records bottom salinities of 31.13 to 32.4 per mille at 45 to 55 meters in St. Marys Bay and 31.2 to 32.2 per mille in 40 to 70 meters depth in Passamaquoddy Bay in the summer of 1916. It is an interesting question, for future solution, whether the bottom salinity of Penobscot Bay and Frenchmans Bay is equally low or whether enough water drifts inward along their troughs to maintain bottom salinities as high as off the open coast.

Little change seems to take place in the bottom salinity of the 40 to 100 meter depth zone along the northern slope of the gulf in autumn, winter, or March. Thus, 14 stations between Cape Cod and the Bay of Fundy averaged about the same at 25 to 80 meters in September and October (32.4 per mille) as in summer, with 4 stations east of Cape Elizabeth averaging 32.7 per mille (extremes of 32.8 and 32.6 per mille) in the midwinter of 1920–21 at 60 to 100 meters. The bottom values for this sector in March, in equal depths, have been 32.4 to 32.5 per mille. Close agreement between the bottom salinity at 40 meters off Yarmouth on January 4, 1921 (31.3 per mille, station 10501), and Vachon's summer records for that locality (p. 769) suggest equal constancy as characteristic of the Nova Scotian side from late summer to midwinter.

Vernal freshening by the rivers and by the Nova Scotian current affects but slightly even the shoaler part of the 40 to 100 meter bottom zone, as described above (p. 750)—the deeper parts hardly appreciably (p. 752). In Massachusetts Bay this event is reflected in a decrease in salinity by about 0.3 to 0.4 per mille from March to May (p. 813), the Bay of Fundy (p. 809) and the eastern side of the gulf, as exemplified by German Bank (p. 814), freshening somewhat more; but it is doubtful whether any vernal freshening of the bottom water from this source is appreciable along the sector between Cape Elizabeth and Mount Desert at depths greater than 100 to 120 meters, except close in to the mouths of rivers (p. 814).

At the end of the winter and in spring we have found the bottom water at this depth varying from 32.5 per mille to about 33 per mille in salinity on the offshore banks, also; and in some years (1916, for example) bottom salinities no higher than this prevail up to the third week in July—perhaps later still; but in other summers (typified by 1914) when slope waters creep in over the shelf during the first two months of summer it raises the bottom salinity to 34 to 34.9 per mille along the southern (offshore) edge of Georges Bank and on Browns Bank.

The zone shoaler than 40 meters falls naturally into two divisions, the one including the waters immediately fringing the coast line of the gulf, the other the greater part of Nantucket Shoals and the shoals on Georges Bank. This zone extends right up to tide line within the gulf, including the shoal bays and river mouths; hence, its bottom water ranges in salinity from brackish, on the one hand, to maximum values of about 32.9 per mille toward its lower boundary, on the other, and experiences the full effects of seasonal freshening. Very little attention has yet been paid to the salinity of this zone around the open gulf; but our stations in Massachusetts Bay in August, 1922, with the Canadian data for the Bay of Fundy region, added to such other evidence as is available, point to about 31 to 32.5 per mille as the usual limits to the bottom salinity at 10 to 40 meters depth in summer and autumn all along the open shores from Cape Cod to Cape Sable, including Casco Bay and the Bay of Fundy. Considerably lower bottom salinities are to be expected over this depth zone in estuaries into which large rivers empty; Vachon (1918), in fact, has recorded values of 28.22 per mille to 31.49 per mille at the mouth of the St. Croix River, varying according to precise locality and stage of the tide, with 31.14 per mille at 20 meters in Kennebecasis Bay and 30.2 to 32.6 per mille at 20 meters at the mouth of the Annapolis River for September, 1916.

The zone from the surface down to a depth of 20 to 30 meters is the only part of the bottom of the gulf that experiences a wide seasonal fluctuation in salinity from the vernal freshening of the surface stratum from the land and from the vernal expansion of the Nova Scotian current. In this shallow water, however, the change in salinity from autumn and winter (when it is near its maximum) to May (when, generally speaking it falls to its minimum) is so wide that the bottom fauna must either be comparatively indifferent to the salinity of the water or able to carry out bathic migrations sufficiently extensive to escape them.

No bottom samples have been collected on the shoal parts of Nantucket Shoals, but neighboring stations suggest 32 to 32.5 per mille as the probable values there at 20 to 40 meters for the summer, autumn, and winter—perhaps slightly lower in spring.

ALKALINITY

It has long been known that under normal circumstances sea water is invariably a very slightly alkaline solution. Within the last few years attention has been attracted to the seasonal and regional variations in the precise degree of alkalinity in the sea by the probability that this feature of the aquatic environment may be one of the controlling factors in the biology of marine organisms, especially of the unicellular planktonic forms. Seasonal changes in this respect also afford a possible measure of the activity of diatom and other plant flowerings, and thus of the intensity of life processes in general in the sea, because marine plants increase the alkalinity of the sea water as they draw carbon from the bicarbonates in solution.

This whole question is exceedingly technical; so much so that no convenient measure for alkalinity has yet been devised, the meaning of which would be obvious to any one who had not devoted some attention to the subject. Salinity, for example, is expressed in percentage or per thousand (the more usual terminology), temperature in degrees—expressions sufficiently familiar to be readily understood. The degree of alkalinity, however, usually is stated in terms of the concentration of the hydrogen-ion, which can hardly be expected to bring a concrete image to the mind of anyone not a trained chemist. Perhaps to the marine biologist or to the oceanographer who is not a trained chemist the following quotation in non-technical language may help to clarify the matter:

> The unit of hydrogen-ion concentration is 1 normal hydrogen-ion per liter of water, or about 1 gram of hydrogen-ion per liter. The finest distilled water contains only about 1 gram of hydrogen-ion in 10,000,000 liters of water at about 22° C., and thus its hydrogen-ion concentration is about 10^{-7}. Sea water, however, is alkaline and contains only about a tenth this concentration of hydrogen-ions. (Mayor, 1919, p. 157.)

The symbol "pH" was invented by Sörensen (1909) and has since been widely adopted to avoid the necessity of writing negative exponents, the notations added thereto being—stated in the baldest possible terms—the logarithm of the reciprocal of the true hydrogen-ion concentration.[20] Therefore, the larger the number of pH the less acid or more alkaline is the water, pH 7 being about neutrality, anything below that acid, and anything above that alkaline.

Determinations of the alkalinity of the sea water can be carried out with little difficulty at sea by the colorimetric method.[21]

The colorimetric tubes used on the *Albatross* in 1920 and on the *Halcyon* were prepared especially for us by Dr. A. G. Mayor and used as prescribed by him (Mayor, 1922, p. 63). These give correct readings for pH if the salinity be 32 to 33 per mille, but for higher salinities every additional 1 per mille of salinity requires a

[20] For a fuller explanation of the reason for expressing the hydrogen-ion concentration by the term pH, rather than directly see Mayor (1919 and 1922), Clark (1920), and Atkins (1922).

[21] McClendon, Gault, and Mulholland (1917) and Mayor (1919) give details as to the preparation and use of the comparator tubes for rough and ready use at sea.

correction of −0.01 of pH, and a correction of +0.01 for every 1 per mille by which the salinity falls below 32 per mille, thus:

Salinity, per mille	Correction to pH
29	+0.03
30	+0.02
31	+0.01
32–33	0
34	−0.01
35	−0.02

For use on shipboard, where conditions of light and shade are not always of the best, and where the lurching of the vessel may make it difficult to handle delicate apparatus, a dark comparator box, in which three tubes can be inserted—the sea water to be tested and a standard on either side of it—much facilitates the comparison of slight differences of color. We have made the following series of determinations from the *Albatross* and *Halcyon*. Accuracy can be expected to ±0.05 of pH, my experience corroborating Mayor's (1922, p. 65) statement that differences as small as 0.03 pH can be detected with the particular colorimetric tubes employed.

Albatross stations

Station	Date	Depth	pH corrected	Salinity, per mille	Temperature °C.
42° 20′ N. by 70° 40′ W.	Mar. 10	Surface	7.9	32.00	----
42° 17′ N. by 70° 07′ W.	do	do	7.9	32.43	2.22
42° 12′ N. by 69° 06′ W.	do	do	7.9	32.65	2.22
20063	Mar. 11	do	7.9	32.61	3.61
	do	190 meters	7.88	34.61	4.63
20064	do	Surface	7.9	32.84	3.5
	do	330 meters	7.98	34.78	4.02
20065	do	Surface	7.9	32.63	3.61
	do	80 meters	7.9	32.69	2.73
20066	do	Surface	7.9	32.57	3.33
	do	70 meters	7.9	32.59	3.53
20067	Mar. 12	Surface	7.9	32.68	3.05
	do	90 meters	7.9	32.79	2.80
20068	do	Surface	7.9	32.65	3.33
	do	150 meters	7.9	33.86	4.40
	do	190 meters	7.89	34.23	4.92
20069	do	Surface	7.9	32.83	3.33
	do	1,000 meters	7.88	34.92	3.77
20073	Mar. 17	Surface	7.9	32.44	2.22
20074	Mar. 19	do	7.9	32.09	1.39
	do	150 meters	7.9	33.69	4.68
20075	do	Surface	8	31.80	.56
	do	90 meters	8	33.21	3.76
20078	Mar. 20	Surface	8	32.45	1.95
20079	Mar. 22	do	7.9	32.56	2.50
	do	200 meters	7.9	33.31	4.29
20082	Mar. 23	Surface	7.9	32.59	2.67
20083	do	do	7.9	32.17	1.95
20085	do	do	7.9	----	2.50
20087	Mar. 24	do	7.9	32.49	3.05
	do	250 meters	7.89	34.22	5.06
20089	Apr. 6	Surface	7.96	31.25	3.05
20090	Apr. 9	do	7.9	32.36	3.33
	do	120 meters	7.9	32.48	2.25
20091	do	Surface	8	31.97	3.33
20092	do	do	7.94	31.01	3.05
20095	Apr. 10	do	8.02	30.07	3.05
20096	do	do	8.02	29.94	2.78
20098	Apr. 11	do	7.95	32.39	3.05
20099	Apr. 12	do	7.99	31.46	3.61
20103	Apr. 15	do	7.9	32.74	3.89
20104	do	do	7.9	32.32	3.05
20107	Apr. 16	do	7.9	32.34	3.33
20108	do	do	7.9	32.58	4.17
	do	130 meters	7.9	33.05	3.75
20109	do	Surface	7.9	32.65	4.17
	do	150 meters	7.88	34.54	6.47

Albatross stations—Continued

Station	Date	Depth	pH corrected	Salinity, per mille	Temperature °C.
20112	Apr. 17	Surface	7.9	32.54	3.61
20113	do	do	7.9	32.50	3.33
20116	Apr. 18	do	8	32.14	3.61
	do	195 meters	7.9	33.91	4.25
20117	do	Surface	8	31.87	3.61
20118	Apr. 20	do	8.05	31.55	4.44
20121	May 4	do	8.18	29.08	5.56
	do	60 meters	8.15	32.24	2.39
20122	May 8	Surface	8.19	28.26	7.22
	do	85 meters	7.9	32.38	2.30
20123	May 16	Surface	8.02	29.94	8.89
	do	55 meters	7.9	32.18	2.35
20124	do	Surface	7.93	29.87	9.72
	do	100 meters	7.9	32.45	2.65
20125	do	Surface	7.92	30.25	9.17
	do	140 meters	7.9	32.21	4.04
20126	May 17	Surface	7.9	31.53	8.33
	do	160 meters	7.9	33.49	4.10
20127	do	Surface	7.9	31.89	7.22
	do	145 meters	7.9	32.98	3.80
20128	do	Surface	7.9	32.98	7.78
	do	70 meters	8	32.50	5.04
20129	do	Surface	7.9	32.61	7.78
	do	160 meters	7.88	34.72	8.28
20130	May 19	Surface	8	33.17	12.22

Halcyon stations

Station	Date	Depth, meters	pH corrected	Salinity, per mille	Temperature, °C.
10488	Dec. 29, 1920	Surface	7.9	31.82	3.89
10631	Aug. 22, 1922	do	8	31.29	17.80
10632	do	do	8	31.21	18.00
	do	73 meters	8	32.37	4.50
10636	Aug. 24, 1922	do	7.9	31.09	15.80

On March 25 and 26, 1919, Mayor (1922) found the alkalinity to be as follows at several stations between Cape Ann and Yarmouth, Nova Scotia:[22]

Locality	pH corrected	Salinity, per mille	Temperature, °C.
10 miles off Cape Ann	8.04	31.75	4.3
47 miles off Boston Harbor	8	32.54	4.2
Near Cashes Ledge	8	32.56	3.5
32 miles off Yarmouth	7.96	31.46	2.2
8 miles off Yarmouth	7.06	31.67	1.4

Henderson and Cohn (1916) found the alkalinity of several Gulf of Maine samples to vary from pH 8.031 to pH 8.102.

Off the Atlantic coast of the United States, between New York and the Tortugas, Mayor (1922) has reported a range of pH from 7.95 to 8.23, noting a characteristic difference between the gray-green coastal water, with a pH of about 8, and the deep blue gulf stream outside the edge of the continent, with a pH upward of 8.2.

The pH as tabulated above shows the Gulf of Maine to fall among the less

[22] For general summaries of the measurements of pH that have been made in various seas, see Clark (1920), Atkins (1922), and Palitzsch (1923).

alkaline seas, as might have been expected from its comparatively low salinity and temperature. Within the gulf, however, the pH from station to station does not correspond to the differences in salinity or in temperature; neither have I been able find any definite parallelism between the pH and the abundance of diatoms—certainly no decided rise even at the times and stations when these pelagic plants are flowering most freely. In short, the volume of water is too large and its circulation too free for any given flowering to reflect its active photosynthesis by an appreciable local rise in pH.

The fact that in March the deeper of two samples was in several cases the more alkaline, but that in May the reverse was true, may be significant, the phytoplankton being most abundant in the well-illuminated strata near the surface. It is not improbable, also, that a larger number of observations carried out through the the year would reveal a seasonal fluctuation of pH, with the maximum in early spring and summer following the vernal flowerings of diatoms and the summer multiplication of peridinians, such as occurs in the Irish Sea[23] (Moore, Prideaux, and Herdman, 1915; Bruce, 1924).

VISUAL TRANSPARENCY

Measurements of the transparency of the water were taken at 18 stations durthe summer of 1912 with the ordinary "Secchi" disk—a metal plate 14 inches in diameter, painted white, and rigged with a bridle, so that it hangs horizontal. This is viewed through a water glass[24] while being lowered, and the depth at which it disappears from view is recorded.

In the clearest water the disk was visible to 8.2 fathoms, but at most of the stations it disappeared at 4 to 5 fathoms. Local variations in transparency did not parallel the variations in color (p. 823), for while the water was most transparent when bluest, it was not least so where greenest, but where the percentage of yellow was only 20 (station 10038).

The transparency does not measure the penetration of sunlight, for water cloudy with silt or with diatoms may still be translucent, like ground or opal glass, though transparent to only a small degree.

Transparency, in meters

Date, 1912	Station	Transparency	Date, 1912	Station	Transparency
July 11	10004	6.4	Aug. 15	10031	7.3
July 17	10011	11	Aug. 20	10036	7.3
July 23	10012b	11	Aug. 21	10037	7.3
July 24	10014	11	Aug. 22	10038	5.5
July 25	10015	8.2	Do	10039	11
July 26	10016	6.4	Aug. 24	10040	9.1
Aug. 7	10022	13	Aug. 29	10043	9.1
Do	10023	15	Aug. 31	10044	9.1
Aug. 8	10025	12			

[23] See Nelson (1924) for an account of rapid diurnal variations of pH in the estuarine waters of New Jersey.

[24] The use of the water glass is necessary to escape the effect of reflections from the surface.

COLOR

The color of the gulf was measured by percentages of yellow[25] during the summers of 1912 and 1913.

As is well known, the water is, as a whole, bluest outside the edge of the continent, greenest alongshore. With only 2 per cent yellow, the water at our outermost station off Nantucket on July 8, 1913 (station 10060), closely approached the pure sapphire blue characteristic of the so-called "Sargasso Sea," of the Mediterranean, and of certain regions in tropical Indian and Pacific Oceans. In our experience the water has never shown as small a percentage of yellow as this anywhere inside the edge of the continent, though with only 5 per cent of yellow off Nantucket Shoals on July 9, 1913, evidently only a slight overflow of tropic water would have been required to produce very blue water. This is the minimum percentage of yellow so far recorded for the Gulf of Maine proper, and three stations for 1913 point to 9 per cent yellow as about normal for the central basin of the gulf.

At the other extreme, we have invariably found the percentage of yellow greatest (27 to 35 per cent) in the coastal belt along the shore of Maine, out, roughly, to the 100-meter contour, with secondary smaller but very green areas (27 per cent of yellow) along the outer side of Cape Cod and in the German Bank region. The greenest water so far recorded has been in Casco Bay, though inclosed locations probably would prove equally green all around the coast line of the gulf. In the western, northern, and eastern parts of the gulf, including the Massachusetts Bay region on one side and the waters off the Bay of Fundy and west of Nova Scotia on the other, the percentage of yellow has usually ranged from 14 to 20.

The Gulf of Maine, like most coastal boreal waters, thus falls among the greener seas, its color agreeing fairly well with that of the English Channel and with the coast water of the Bay of Biscay (Schott, 1902, pl. 36). However, as I have noted in earlier publications (Bigelow, 1914, p. 81; 1915, p. 225), the distribution of color does not exactly parallel either the temperature or the salinity, for while low salinity is reflected in a high percentage of yellow, the most saline part of the basin has not been the bluest. The true key to local variations in color within the gulf is to be found more in variations in the density and character of the plankton and in the amount and nature of the silt which the water holds suspended.

The records for the two years combined show that the color of the gulf changes but little from July to August or from year to year at that season. No measurements of the color have been made at other times of year, but a browner hue is to be expected alongshore when diatoms are flowering actively in spring.

---

[25] The color of the sea usually is measured by the "Forel" scale, based on a combination of blue and yellow, the former being 5-gram copper ammonia sulphate + 0.5 cubic centimeter ammonia in 95 cubic centimeters water; the latter 15-gram potassium chromate in 100 cubic centimeters of water. The combinations used are as follows:

	1	2	3	4	5	6	7	8	9	10	11	12	13
Per cent blue	100	98	95	91	86	80	73	65	56	46	35	23	10
Per cent yellow	0	2	5	9	14	20	27	35	44	54	65	77	90

Various comparators have been devised for use on shipboard. For descriptions of the method employed on the *Grampus* see Bigelow, 1914, p. 38.

Date	General locality	Station	Color in percentage of yellow
1912			
July 10	Off Gloucester	10002	20
11	Near Gloucester	10004	20
13	Off Boston Harbor	10006	20
15	Basin off Cape Ann	10007	14
16	Ipswich Bay	10008	20
16	Northeast of Cape Ann	10009	14
16	Off Hampton, New Hampshire	10010	20
17	Near Isles of Shoals	10011	20
24	Off Kennebunkport	10013	27
24	do	10014	27
25	Casco Bay	10015	27
26	Near Seguin Island	10016	27
27	Casco Bay	10017	35
27	Orrs Island		44
29	Off Casco Bay	10019	20
Aug. 2	Off Monhegan Island	10021	27
3	Penobscot Bay	10021a	27
7	Off Cape Elizabeth	10022	27
7	Platts Bank	10023	14
8	Offing of Penobscot Bay	10025	20
8	Off Matinicus Island	10026	20
8	Near Seguin Island	10026a	20
14	Basin South of Mount Desert	10027	20
14	Basin, east side	10028	20
14	German Bank	10029	20
15	Off Lurcher Shoal	10031	24
16	Off Mount Desert Rock	10032	24
16	Off Machias, Me	10033	35
19	West end, Grand Manan Channel	10035	20
20	Offing of Machias, Me	10036	20
21	Near Mount Desert Island	10037	35
21	Off Isle au Haut	10038	20
1913			
July 8	Off Northern Cape Cod	10057	27
8	Southwestern part of basin	10058	9
9	West side of Georges Bank	10059	20
9	Offing of Nantucket Shoals	10060	5
10	Continental edge, off Nantucket Shoals	10061	2
Aug. 4	Off Chatham, Cape Cod	10085	27
5	Off northern Cape Cod	10086	27
9	Off Gloucester	10087	14
10	Center of basin	10090	9
11	Offing of Penobscot Bay	10091	20
11	East side of basin	10092	9
12	do	10094	27
12	German Bank	10095	27
12	Off Lurcher Shoal	10096	20
13	Off Machias, Me	10098	20
13	Near Mount Desert Island	10099	27
13	Near Mount Desert Rock	10100	27
14	Offing of Penobscot Bay	10101	35
14	do	10102	20
15	Near Isles of Shoals	10104	20
15	Offing of Ipswitch Bay	10105	20

SOURCES FROM WHICH THE GULF OF MAINE RECEIVES ITS WATERS

In few parts of the world is the coast water that bathes the continental shelf as sharply demarked from the oceanic water outside the edge of the continent as it is off the east coast of North America, from the Grand Banks on the north to Cape Hatteras on the south. Not only is the former much colder and much less saline than the latter, but the transition from the one type to the other is often remarkably abrupt. To see the warm sapphire blue of the so-called "Gulf Stream" give place to the cold bottle-green water over the banks is a familiar spectacle to mariners sailing in from sea. While it is unusual to meet as abrupt a transition as Smith (1923, pl. 5) describes for one occasion (March 27, 1922) south of the Grand Banks, where the water changed from a temperature of 1.1° to 13.3° C. (34° to 56° F.) within the length of the ship, and where the line of demarkation between the two waters was made plainly visible on the surface by ripplings, the transition zone from the one to the other is usually compressed within a few miles abreast the Gulf of Maine.

The general characteristics of the coast water in boreal latitudes have been well described by Schott (1912) and are matters of common knowledge. I need merely state here that mean annual surface temperatures lower than 15° and mean salinities lower than about 33.5 per mille may be so classed, as distinguished from the much warmer and more saline (35.5 per mille) tropic water, which is commonly (though rather loosely) termed "Gulf Stream" as it skirts the North American plateau.

In discussing the sources of the sector of the coast water included within the Gulf of Maine, it will be convenient to consider the upper and lower strata separately, for it is now proven they they draw chiefly from different sources.

SUPERFICIAL STRATUM

NOVA SCOTIAN CURRENT

Until detailed study of the physical characters of the coast water off northeastern North America was undertaken by the United States Bureau of Fisheries, the Museum of Comparative Zoology, and the Biological Board of Canada, a northerly source was usually ascribed to the coastal water all along the seaboard of Nova Scotia, New England, and much farther to the south. This, in fact, has been described, time out of mind, as the "Arctic current." As I have remarked in an earlier report (Bigelow, 1915, p. 251), "almost all the ocean atlases show something of this sort; and it has been accepted in one form or another in almost all the textbooks on physical geography and oceanography (for example, Maury, 1855; Reclus, 1873; Attlmayr, 1883; Thoulet, 1904; Krümmel, 1911; Schott, 1912; the German Marine Observatory (Deutche Seewarte, 1882), the current charts of the United States Navy (Soley, 1911), and the British Admiralty (1897) current chart.)"

The low temperature of the surface water near shore, contrasted with the "Gulf Stream" offshore and with the oceans as a whole at the latitude in question, naturally suggests a northern origin until analyzed in relation to other factors (p. 686). Ostensible evidence to the same effect is afforded by the continuity of the cold zone all along the northeastern coasts of North America, with its mean temperature gradually decreasing from the south toward the Newfoundland-Baffins Bay region in the north. The southwesterly drift that has been reported repeatedly along the coasts of the northeastern United States and Nova Scotia argues in the same direction; so, also, the extension of a generally boreal fauna southward and westward as far as Cape Cod, with planktonic communities of this category spreading still farther in this direction in winter.

The observations on the temperature, salinity, and circulation of the gulf, detailed in other chapters, do, in fact, prove beyond reasonable doubt that water from the northeast (low in temperature) does flow past Cape Sable into the Gulf of Maine for a time in spring, sometimes into the summer. Before considering what part this actually plays in the Gulf of Maine complex a few words may well be devoted to its probable source.

Up to 1897 the supposed coldness of the coastal water along North America in general, and any definite evidences or reports of a current from northeast to southwest in particular, were usually classed as southward extensions from the Labrador Current. Without much analysis this Arctic stream was generally thought to flow down from the Grand Banks region, past Nova Scotia, and so southward along the whole eastern seaboard of the United States, carrying to New England the cold resulting from the melting of ice (floe and berg) in Baffins Bay or about the Grand Banks. Some such southerly branch of the Labrador Current is taken for granted in most of the older textbooks, charts, and discussions of North American hydrography. Thus Libbey (1891, 1895), in his studies of temperature south of Marthas Vineyard, definitely identified as such the cool band that he recorded along the continental edge in the offing of southern New England. This view was widely held until recently. Sumner, Osburn, and Cole (1913, p. 35), for example, state, on the authority of the United States Navy Department, that the Labrador Current flows from the Grand Banks past Nova Scotia and so southward as far even as Florida, narrowing from north to south. Krümmel (1911) believes the polar water tends to drift southwestward across the Grand Banks and so to Nova Scotia. Engelhardt (1913, p. 9, chart B) did not doubt that the Labrador Current bathes our coasts at least as far as the Gulf of Maine. Johnston (1923, p. 271) describes it as hugging the coast of North America from Halifax to Cape Cod; and as recently as 1924 Le Danois (1924, p. 14) wrote of the "dernierès eaux du courant du Labrador qui longuent la côte des Etats Unis."

On the other hand, Verrill (1873, p. 106; 1874), in the early days of the United States Fish Commission, had maintained that the actual temperatures of the deep strata of the Gulf of Maine did not suggest the effects of any Arctic current, though he qualified this generalization by adding that the gulf receives accessions of cold water, ultimately coming from the north, by the tides.

It is obvious that for the Labrador Current to follow the track usually ascribed to it implies a dominant cold drift setting southwestward from the Newfoundland-Grand Banks region across the oceanic triangle that separates the Newfoundland from the Scotian Banks, and so in over the latter toward the coast; but although a current of this sort is represented on many charts, its supposed extension westward from the Grand Banks to Nova Scotia seems to have been based more on theoretic grounds (the assumed necessity for connecting the cool coastal water to the southward with the Arctic flow from Baffins Bay) than on direct observation. Schott (1897), who first attempted a detailed study of oceanography of the Grand Banks region, also failed to find any dominant set from northeast to southwest across the banks, in spite of the proximity of the Labrador Current, which has long been known to skirt their eastern edge and sometimes to round the so-called "tail of the bank" for a short distance westward and northwestward. He did, it is true, record sporadic movements of this Arctic water in over the banks, but he believed them too small in volume and too irregular in occurrence to be anything but temporary surface currents caused by the northeast winds, which often blow fresh there. His conclusions were based on so many records of temperature and on measurements of the current taken from fishing vessels lying at anchor on the banks that they form the foundation for more modern knowledge of the characteristics of the Labrador Current in the Grand Banks region.[26]

Schott's chief thesis—that the most southerly bounds of the Labrador Current as a definite stream flow lie not far south or west of the "tail" of the Grand Banks—has been corroborated by the extensive oceanographic observations taken yearly by the International Ice Patrol since 1914 (Johnston, 1915; Fries, 1922 and 1923; E. H. Smith, 1922 to 1927; Zeusler, 1926), both in the region of the banks and in the oceanic triangle between the latter and Nova Scotia; also by the drift-bottle experiments carried out by the Biological Board of Canada (Huntsman, 1924).

The data gathered by the Ice Patrol are especially instructive in connection with the Gulf of Maine, both because of their extent and because especial effort has constantly been made to chart any extensions of the Labrador Current that might carry bergs toward the west or southwest—extensions usually easily traceable by their icy temperature, even if carrying no bergs with them at the time. Furthermore, the operations of the patrol cover the part of the year (March to July) when the Labrador Current is greatest in volume as it flows southward and lowest in temperature—hence, when it would be most likely to reach the coast line of Nova Scotia or the Gulf of Maine, if it ever does so.

So many oceanographic sections have now been run in various directions from the tail of the Grand Banks by the patrol in various years, and between the banks and Halifax, with so careful a record of all bergs since 1911, whether actually sighted by the patrol cutter or reported by other ships (E. H. Smith, 1924a, chart M), that it is hardly conceivable that any considerable or constant flow of icy cold water from the Grand Banks region toward Nova Scotia could have escaped attention during the seasons covered.

Actually, however, not a single phenomenon of this sort has been encountered during all the years of the patrol. Thus, Johnston (1915, p. 41), in his report on the operations of 1914, definitely states that "as a stream, Labrador water never gets west of Grand Bank"; consequently, that the name "Labrador Current," as applied to the cold water along the eastern coast of the United States, is a misnomer. Fries (1922, p. 73), in discussing the oceanographic observations during the patrol of 1921, also failed to find any evidence of the Labrador Current continuing westward from the Grand Banks toward the Gulf of Maine. With the accumulated data of successive years, E. H. Smith (1923) describes the Labrador Current as usually reaching its farthest boundary on the south and west, somewhere between latitude 42° and 43°, longitude 51° and 52°, where it eddies sharply to the eastward. A similar account has recently been given by the Hydrographic Office, United States Navy (1926). As this was the case during the spring and early summer of 1923 (a year that may be classed as normal, both in respect to the number of ice bergs that drifted down to the tail of the Grand Banks and to temperature), and again in the ice-free season of 1924, E. H. Smith (1924a, p. 144) seems fully justified in his conclusion that when the Labrador Current recurves westward around the tail of the banks this is "the extreme

[26] Schott (1897) described small amounts of polar water as turning westward past Cape Race along the south coast of Newfoundland, to enter the Gulf of St. Lawrence via the northern side of Cabot Strait, where an inflowing current (i. e., setting west) has often been reported. More recent studies, however, have made it seem unlikely that it extends so far.

southern extension of the cold polar water." [27] Observers who have actually studied oceanographic conditions first hand in the Grand Banks region are unanimous to this effect.

The evidence of temperature and salinity on which this general thesis rests is set forth in detail in the successive reports of the patrol (see also Bjerkan, 1919; Le Danois, 1924, p. 40, and 1924a, p. 46) and need not be repeated here. I need only point out that any branch of the Labrador Current that might flow southward from the banks would not only be betrayed by its temperature and salinity (p. 829) but it would doubtless carry bergs with it in greater or less number from time to time. Actually, however, not a single berg (except small ones drifting out from the Gulf of St. Lawrence) was reported west of longitude 55° during the period from 1911 to 1924, very few west of longitude 52°, whereas some hundreds came drifting down along the east slope of the Grand Banks during that period (see E. H. Smith, 1924, chart P, showing distribution of ice bergs from 1911 to 1923).

The results of the drift-bottle experiments carried out in eastern Canadian waters within the past few years by the Biological Board of Canada have not yet been published in detail. However, Dr. A. G. Huntsman kindly supplies the information that they give no more suggestion of a definite stream from the Grand Banks toward Nova Scotia than do the temperatures or ice drifts just discussed.[28]

In short, no actual evidence of such a current is forthcoming from recent investigations, but the reverse. I have no hesitation, therefore, in definitely asserting that the Labrador Current does not reach, much less skirt, the coast of North America, from Nova Scotia southward, as a regular event, corroborating Jenkins's (1921, p. 166) statement that it does not reach the coast of the United States. Consequently this is not the direct source of the cold current that reaches the Gulf of Maine from the east. If overflows of the Labrador Current do take place in this direction they are of such rare occurrence that no event of this sort has yet come under direct scientific observation.

As Huntsman (1924, p. 278) points out, a certain amount of the water flowing down from the Arctic may move westward and southwestward along the slope of the continent as a constituent of the slope water (p. 842), so much warmed, however, en route, by mixture with tropic water that if it reaches the Gulf of Maine at all it does so as a warming and not as a cooling agent, and on bottom, not at the surface. Labrador Current water in small amount may also reach the gulf indirectly via the Gulf of St. Lawrence route, shortly to be discussed; but if so, its distinguishing characters as an Arctic current are lost, and it becomes one of the constituents of a coastal current.

The physical characters of the cold band of water that hugs the outer coast of Nova Scotia also forbid the idea that it draws direct from the Labrador Current. According to the observations by the *Scotia* (Matthews, 1914), the records of the Canadian Fisheries Expedition of 1915 (Bjerkan, 1919), and the much more extensive data that have been accumulated during the years of the Ice Patrol, the

---

[27] The reader is referred to Smith's chart (1924a, sketch 10, p. 150) for the normal distribution of the Arctic water around the banks in the spring and early summer; also to his general scheme of circulation in the vicinity of the tail (Smith, 1924a, p. 135).

[28] Huntsman's chart (1924, fig. 32) showing the complexity of the circulation between Nova Scotia and Newfoundland includes the most outstanding results of these experiments.

unmixed Labrador Current (temperature below $-1°$) is colder than the coldest outflow from Cabot Strait, or than the coldest water over the Scotian shelf, which have never been found to fall below $-0.5°$ in temperature. The evidence of salinity, of like import, is even more instructive in this respect, for the undiluted Labrador Current off the Grand Banks is considerably more saline than the cold water next the Nova Scotian coast, being characterized by a salinity of at least 32.5 per mille, while its surface salinity hardly falls below 32 per mille even along its inner edge, where most influenced by drainage from the land (minimum so far recorded about 31.9 per mille; Matthews, 1914).

"From this," as I have stated elsewhere (Bigelow, 1917, p. 236), "it appears that did any considerable amount of unadulterated Labrador water join the Nova Scotia coast current, the temperature of the latter would be lower, its salinity higher, than in Cabot Straits"; whereas both the temperature and the salinity of the cold band skirting the Nova Scotian coast have proved remarkably uniform, from the straits westward to its farthest extension. It is true that an infusion of Labrador Current water (spreading westward from the Grand Banks region) might join the Nova Scotian coast water without lowering the temperature of the latter did it mix sufficiently with the warmer water, which it must needs displace en route, to raise its own temperature by 1° or more. Such a mixture, however, would necessarily raise its salinity as well as its temperature, because the water that normally fills the deep oceanic triangle between the Scotian and Newfoundland Banks is considerably more saline than the Labrador Current, a fact amply demonstrated by repeated profiles run by the Ice Patrol and by the Canadian Fisheries Expedition (Bjerkan, 1919). Hence, if any large amount of such mixed water joined the cold Nova Scotian coast current, the salinity of the latter would be made considerably higher than it actually is, so that salinity would betray the event even if temperature did not. Actually nothing of the sort has been recorded, observations taken by the *Grampus*, the Canadian Fisheries Expedition, and the Ice Patrol uniting to demonstrate that low salinity is as characteristic of the cold band next Nova Scotia as low temperature is. However, the temperatures and salinities taken by the *Acadia* in July, 1915 (Bjerkan, 1919), make it at least highly probable that isolated offshoots, pinched off as it were from the Labrador Current, do occasionally drift westward as far as the continental slope off Banquereau Bank and Cape Sable. Otherwise it would be difficult to account for the pool of icy water ($-1.7°$) then reported off Sable Island—a pool both colder and more saline (32.82 to 33.08 per mille) than the outflow from the Gulf of St. Lawrence, but which reproduced the coldest water of the Newfoundland Banks in its physical character.

These several lines of evidence forbid the possibility that the Labrador Current is directly responsible for the low temperature of the cold water that reaches the Gulf of Maine from the east. Water from the Labrador Current may reach the Gulf of Maine indirectly via the discharge from the Gulf of St. Lawrence, for a certain amount of this Arctic water may enter the latter along the northern side of Cabot Strait. Huntsman's (1925) recent survey of the Straits of Belle Isle points to a greater inflow of Arctic water by this route than Dawson's (1907) earlier survey had suggested; but even so, it is an open question whether this Arctic contribution is sufficient to lower the temperature of the coldest stratum of the Gulf of St. Lawrence (or of its discharge around Cape Breton) below the point to which winter chilling, *per se*, and ice melting *in situ*, would reduce it.

Schott (1897) and Hautreaux (1910 and 1911), abandoning the Labrador Current, saw in the Gulf of St. Lawrence the source of the cold coast water as far west and south as New York. This view is supported by so much evidence that in earlier publications (Bigelow, 1915, 1917, and 1922) I have described the cold Nova Scotian water that flows past Cape Sable into the Gulf of Maine as probably a direct continuation of the current that is known to flow out through Cabot Strait on the Cape Breton side.

Briefly stated, the evidence on which this view was based stood as follows up to 1922, when Canadian experiments with drift bottles threw new light on the subject:

The enormous volume of fresh water poured yearly into the Gulf of St. Lawrence by its tributary rivers, added to a deep current of slope water flowing in through Cabot Strait on the bottom (Huntsman, 1924), apparently, too, with a balance of inflow over outflow in the Straits of Belle Isle, and with the currents on the north side of Cabot Strait usually inward, while the rain that falls on the surface of the Gulf of St. Lawrence almost certainly exceeds the evaporation therefrom, make it certain that the current flowing out via the south side of Cabot Strait discharges a large volume of water. Experimental evidence substantiates this, for current measurements by the tidal survey of Canada (Dawson, 1913) seemed to establish a constant outflow there, at least 30 miles broad abreast of Cape North, with an average velocity of about half a knot per hour at the surface, which Dawson (1913) termed the "Cape Breton current," but was earlier known as the "Cabot current."

Temperatures and salinities taken by the *Grampus* in the eastern side of the Gulf of Maine, near Cape Sable, and as far east along the outer coast of Nova Scotia as Halifax, in 1914 and 1915, pointed to a direct continuation of this "Cape Breton" or "Cabot" current southwestward alongshore, nearly to the Gulf of Maine, during these summers (Bigelow, 1917, p. 234). Futhermore, a dominant surface drift of ⅓ knot per hour toward the southwest was recorded by the Ekman current meter off Shelburne, on July 27 and 28, 1914 (station 10231), only 30 miles east of the entrance to the Gulf of Maine.

Thus the physical character of the water, combined with readings of the current meter, seemed to show a direct surface drift from the northeast along the Nova Scotian coast between Shelburne and Halifax, distinguishable by a considerable difference in temperature and salinity from the salter, warmer water that bounded it on the seaward side. These characteristics and the fact that we found such characteristically Arctic components as *Limacina helicina* and *Mertensia ovum* among its plankton seemed to classify it as actually the southernmost prolongation of the outflow from Cabot Strait (Bigelow, 1917, p. 357).

Observations taken by the Canadian Fisheries Expedition of 1915 (Bjerkan, 1919) and returns from several series of drift-bottle experiments subsequently carried out by the Biological Board of Canada in the years 1922, 1923, and 1924[29] have proven the circulation over the continental shelf along Nova Scotia to be of a nature much

[29] Huntsman, 1925, and notes kindly contributed by him

more complex than the simple stream flow from northeast to southwest suggested by the earlier evidence.

The track followed by the ice drifting out of the Gulf of St. Lawrence is especially instructive here in this connection, because this discharge takes place in spring (chiefly in April and May) just when the Nova Scotian current is flooding past Cape Sable into the Gulf of Maine in greatest volume; whereas most of the drift-bottle experiments have been carried out in summer, when this current is usually inactive or at least is carrying so small a volume of water past Cape Sable that it is no longer an important cooling agent for the Gulf of Maine. According to Johnston (1915), the ice that comes out along the Cape Breton side of Cabot Strait does not tend to follow the Nova Scotian coast around to the southwest, as it would if the outflowing current hugged the coastline, but divides. Part drifts out to the southeastward; but the ice that emerges from the gulf nearest the Cape Breton coast moves southward across Banquereau Bank, where it fans out, to the offing of Halifax.

These lines of dispersal correspond very closely with the icy water which Bjerkan's (1919) data for May, 1915, show spreading out from the southern side of Cabot Strait to the region of Misaine and Banquereau Banks (fig. 167), but separated from the still colder (−1°) water on the Newfoundland Banks by a warmer (0°) core in the axis of the Laurentian Channel, and with much higher temperatures off the mouth of the latter. Especially suggestive, from the standpoint of the Gulf of Maine, is the narrow icy tongue (0° to −0.2°) that then extended westward along Nova Scotia past Halifax; a band comparatively uniform, also, in salinity from east to west (31.5 to 32.5 per mille) and considerably less saline than the still colder water on the Newfoundland side of the Laurentian Channel (temperature lower than −1°; salinity 32.7 to 33.2 per mille). This the Ice Patrol cutter had also crossed on her run in to that port about a week earlier (United States Coast Guard stations 26 and 27, May 20, 1915).

Lacking data in the offing of Cape Sable, it is not possible to state whether this cold tongue actually extended to the Gulf of Maine that May, though it may have done so earlier in the season and certainly does so during the spring in some years (p. 681).

A similar concentration of cold water close in to Nova Scotia appears from the temperatures taken by the Ice Patrol along a line from Halifax toward Sable Island in spring in other years. The records for 1919 are especially instructive, showing this band widest at the end of March, when the whole column of water next the land was fractionally colder than zero from the surface to bottom; smaller in volume in April, when it was overlaid by slightly warmer (0° to 1°) water; and shrunken to a narrow tongue on the bottom not more than about 20 miles broad in May.[30]

Drift bottles set out by the United States Coast Guard cutter *Tampa* (Capt. W. J. Wheeler) on April 18, 1924, along a line running 119° (about SE x E½ E.) true from a point about 18 miles southeast of Sable Island (43° 48′ N.; 59° 26′ W.) for 50 miles, likewise show a drift from this region first northward toward the land and then westward toward the Gulf of Maine, three out of the seven returns (all from the inner end of the line) being from Sable Island, one from the Nova Scotian coast not far

[30] The March profile also cut across the southwestern edge of the icy Cape Breton-Banquereau pool near Sable Island.

from Halifax, and one from Gloucester Harbor, where it was picked up on August 14.[31] Although two of the bottles from this line drifted to Newfoundland, showing a division, this does not detract from the evidence of the Gloucester recovery.

Clearer evidence that the cold tongue that skirts Nova Scotia and flows past Cape Sable into the Gulf in Maine in spring is actually an overflow from the icy pool that develops from Cabot Strait out over Banquereau Bank, when the ice is coming out of the Gulf of St. Lawrence, could hardly be asked than results from the temperatures, salinities, and bottle drifts just discussed.

I believe it now sufficiently demonstrated that while this cold pool (fig. 167) owes its low temperature, to some extent, to the direct outflow of icy water from the Gulf of St Lawrence via the Cape Breton side of Cabot Strait, it more directly mirrors the chilling effect of the field ice from the Gulf of St. Lawrence as this melts in the region between Banquereau Bank and Sable Island. Consequently, cold water that reaches the Gulf of Maine from the east is, in fact, ice-chilled, though this takes place 300 miles or more to the eastward of the eastern portal to the gulf.

It is to this cold band skirting Nova Scotia that the name "Nova Scotian current" is applied in the preceding pages. During the spring a large volume of water enters the eastern side of the Gulf of Maine from this source, producing the effects on salinity and temperature described in the chapters on those physical features; and this is certainly the chief source that contributes cold water of northern origin to the Gulf of Maine—almost certainly the only source making a contribution of this sort sufficient in amount and cold enough to exert any appreciable effect on the temperature of the gulf (p. 682).

This current flows into the gulf in volume during only a few weeks in spring—earlier in some years, later in others. As its fluctuations are referred to repeatedly in the preceding pages a summary will suffice here.

In 1920 (a late season) icy water ($<1°$) from this source had spread westward as far as the offing of Shelburne, Nova Scotia, by the last week in March; but neither the temperature nor the salinity of the eastern side of the Gulf of Maine give any evidence that it had commenced to flood past Cape Sable up to that date, nor do the isohalines for that April suggest any drift of water of low salinity into the gulf from the east. The coastal zone, also, warmed about as rapidly in the one side of the gulf as in the other during that month (p. 553). Conditions seem, then, to have remained comparatively static off Cape Sable through the first two months of the spring of 1920, and if the Nova Scotian current discharged at all into the gulf in that year this did not happen until May or later. In 1919, however, an early season, its western expansion culminated before the last of March, and had slackened, if not ceased, by the end of April (p. 558). In this respect 1915 seems to have been intermediate (so may be taken as a representative spring), with the Nova Scotian current exerting its chief chilling effect on the eastern side of the gulf before the first week in May (p. 560), and slackening from May to June, as indicated by the contraction (to the eastward) of the area inclosed by the surface isohaline for 32 per mille (cf. fig. 120 with fig. 128).

[31] Information kindly supplied by Dr. A. G. Huntsman.

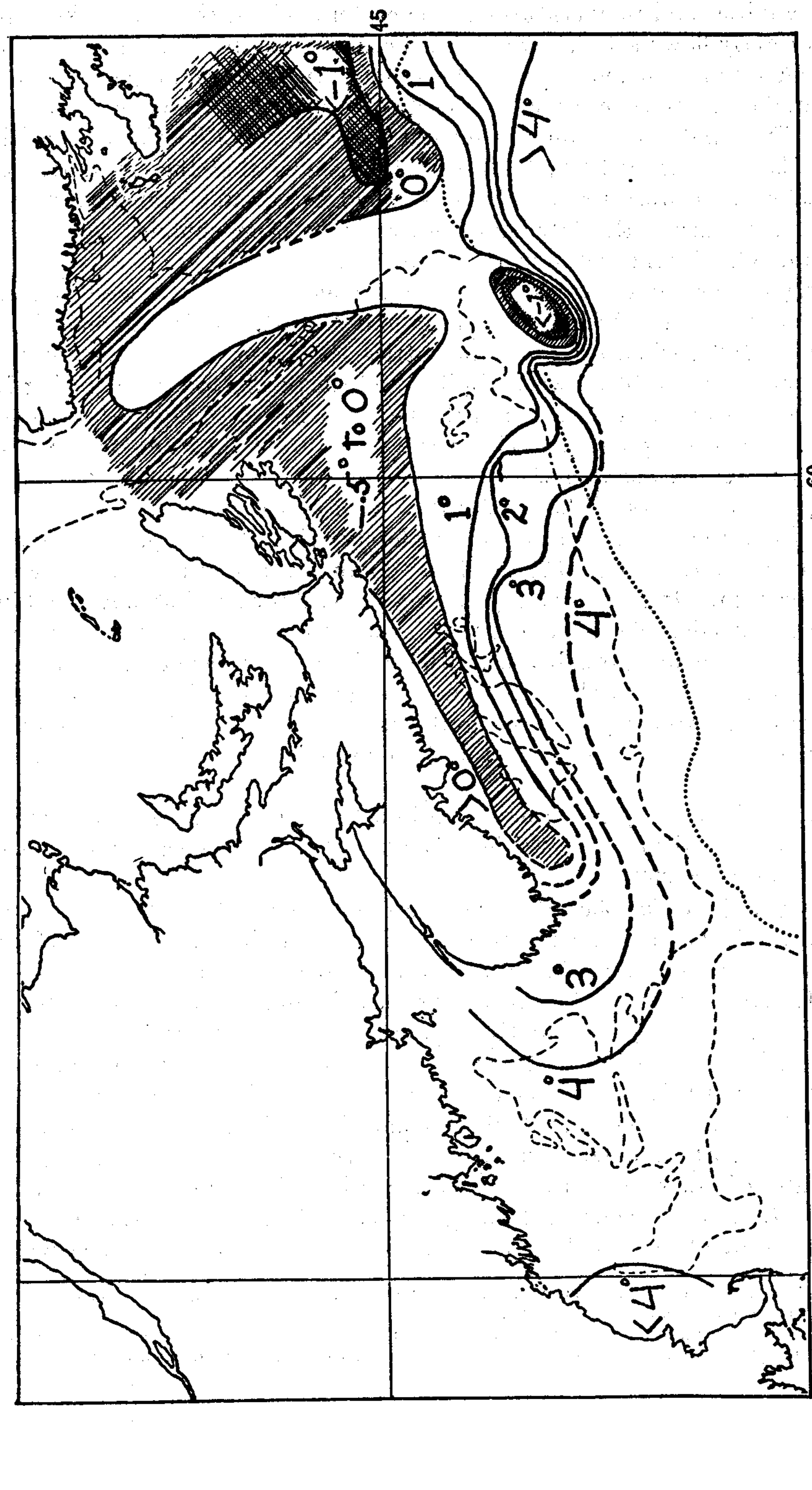

FIG. 167.—Distribution of the coldest water, irrespective of depth, from Newfoundland to the Gulf of Maine, for May, 1915, based on the records of the Canadian Fisheries Expedition (Bjerkan, 1919) and *Grampus* stations 10266 to 10279

The salinities and temperatures of the eastern side of the gulf make it probable that the westerly flow past Cape Sable slackens or ceases by June, at the latest, every year—often a month or more earlier than that. In some years sporadic movements of water undoubtedly take place from east to west past the cape later in the season; but the drift of bottles put out on several lines off Nova Scotia by the Biological Board of Canada during 1922, 1923, and 1924 shows that the circulation over the continental shelf between Browns Bank and the Laurentian Channel becomes exceedingly complex during the late summer, variable from summer to summer, and largely controlled by the contour of the bottom.[32]

During some summers a rather definite current from east to west persists along the Nova Scotian coast right through July and August. This statement is based on the drifts for 1924, when a number of bottles set out on three lines normal to the general trend of the coast between Halifax and the Straits of Canso, during July and August, were picked up in autumn in the Gulf of Maine. Many other bottles from the most easterly lines also traveled westward during that summer but stranded before they reached Cape Sable.[33]

The probable tracks of the bottles that went westward, localized some 12 to 25 miles out from the land, correspond so closely with the tongue of coldest water charted for May, 1915 (fig. 167), that the dominant drift was evidently essentially the same for both. In May, as temperatures show, this east-west movement involved a stratum of considerable thickness; but in the summer of 1924 it was more strictly a surface phenomenon, probably with the underlying water circling offshore along Roseway and La Have Banks in the more usual anticlockwise eddy, because what few temperatures were taken in the gulf that summer (p. 996) suggest no greater transference of cold water (such as a bottom current past Cape Sable would entail) than usual.

The westerly set may again have continued past Cape Sable until September in 1926, when many drifts were recorded from the offing of the cape into the gulf, as summarized on page 909.

The bottle drifts for the other summers of record show, however, that it is unusual for the Nova Scotian current to persist as a definite stream-flow as far west as Cape Sable after June, but that the deep basin between Sable Island Bank on the east and La Have Bank on the west is usually dominated (in summer) by an anticlockwise eddy named by Doctor Huntsman the "Scotian eddy," similar to, though not as extensive as, the eddy that dominates the basin of the Gulf of Maine.

In summers of this type whatever drift takes place intermittently around Cape Sable into the eastern side of the Gulf of Maine draws from what Doctor Huntsman describes as a sort of dead-water region off the cape. True, this, in its turn, receives water of low temperature from the Scotian eddy, but also from the warmer slope water that drifts westward along the edge of the continent, as appears from the recoveries of Canadian drift bottles. Consequently, the surface water that

---

[32] Only a preliminary statement of the general results has yet appeared (Huntsman, 1924); but Doctor Huntsman has very kindly allowed quotation from his unpublished notes.

[33] The account of these experiments contributed in advance of publication by Doctor Huntsman also shows complex drifts inshore and to the eastward for many bottles set out off County Harbor and off Beaver Harbor, which need not be discussed here.

enters the eastern side of the Gulf of Maine in summers of this type is not cold, but actually is warmer than the water it meets within the gulf.

This we found to be the case in July and August of 1914, when salinities and temperatures showed that the cold tongue was eddying offshore toward the edge of the continent, and to the left, a short distance east of the longitude of Cape Sable (Bigelow, 1917), although a dominant southwesterly set of about 1 knot per hour was then recorded in the offing of Shelburne (station 10231). The observations taken during the last week of July, 1915, by the Canadian Fisheries Expedition (Bjerkan, 1919), corroborated by our own September stations for that year (10312, 10313, and 10314), again showed the coldest and least saline water as veering southward from the offing of Shelburne toward La Have Bank—not continuing westward to Cape Sable.

The summer of 1922 seems also to have belonged to this category, because, as Doctor Huntsman informs me, not one of the bottles that were put out to the eastward of Shelburne, Nova Scotia, during that summer has been reported from the Gulf of Maine; but a series set out on a line running southwesterly for 125 miles from Brazil Rock, just east of Cape Sable, on the 17th of that July, evidently coincided with the zone of transition between the Scotian and Gulf of Maine eddies, because about as many bottles from the inner end of the line were reported from the Gulf of Maine and Bay of Fundy (p. 908) as from the eastward, while more either drifted inshore or remained stationary.[34]

Four others, set out near the outer edge of the continental shelf, were picked up on the west coast of Nova Scotia, in the Bay of Fundy, and on the coast of Maine. The latter drifts, Doctor Huntsman points out, indicate a westward tendency along the edge of the continent and entrance into the gulf around or across Browns Bank with the slope water discussed below (p. 842). Such of the bottles from this line as finally drifted into the Gulf of Maine eddy traveled with considerable speed (p. 847); but so many of them worked slowly shoreward, and the dispersal was so nearly equal in the two directions, east and west, that the water off Cape Sable is described by Doctor Huntsman as "a relatively dead zone" at the time, so far as any nontidal drift is concerned. Tidal currents, however, run with great velocity in this region, especially close in to land.

A dead zone of this same sort seems again to have developed off Cape Sable during the summer of 1923, when, as Doctor Huntsman writes, some bottles from a line running eastward from Browns Bank toward La Have Bank (i. e., at right angles to the Cape Sable line of the year previous) were finally recovered in the Gulf of Maine after drifts no more rapid than those of the 1922 series, while others were picked up on the other side of the Atlantic (England, Ireland, France, and the Azores) a year later. The only bottle from lines east of La Have Bank, which is known to have reached the Gulf of Maine during that summer, was one set adrift in Cabot Strait on July 18 and picked up near Cape Sable on December 2. This bottle, Doctor Huntsman suggests, may have gone out along the western side of the Laurentian Channel, then westward along the edge of the continent, and so

[34] Doctor Huntsman kindly allows quotation of these results in advance of publication. They are discussed more fully in another chapter (p. 908).

finally northward toward the Gulf of Maine, via Browns Bank and the Cape Sable dead water.

In years such as those just described the region in the offing of Cape Sable, out to Browns Bank, between the two major circulatory eddies (Scotian and Gulf of Maine) but not directly within the sweep of either, is evidently the site of a very active mixing of waters of diverse origins. Under such conditions a very abrupt east-west transition in temperature and salinity develops off the cape, proving that the westerly (inshore) component of the Scotian eddy is not the motive power for such water as does then flood into this side of the Gulf of Maine. This eddy, on the contrary, is clearly outlined by the surface salinity for July and August, 1914 (Bigelow, 1917, fig. 18), and for June, 1915, as swinging offshore toward La Have Bank, which prevents it from flooding westward through the Northern Channel, toward which the rotation of the earth would direct it, did the contour of the bottom allow.

The strong tidal currents off southern Nova Scotia must tend, however, to pump water from the Cape Sable deadwater into the gulf, because the flood, running westward at a mean velocity of 1.4 knots (Dawson, 1908, station R; a journey of something like 8½ miles for any given particle of water), must follow westward and northward around Cape Sable as it is forced to the right against the shore by the effect of the earth's rotation. With the ebb similarly deflected to the right, a clockwise movement around the rounded outline of southwestern Nova Scotia naturally results, such as eddies around any submerged shoal in high northern latitudes.

TROPIC WATER

We may next consider the possibility that overflows of the surface stratum of tropical or "Gulf Stream" water, the inner edge of which always lies within a few miles of the edge of the continent, may enter the Gulf of Maine from time to time; also possible movements of the coast water from west to east past Cape Cod into the gulf, either via Vineyard Sound or around Nantucket Island. Water from either of these sources would reach the gulf as warm currents, contrasting with the cold Nova Scotian current, the former high in salinity, the latter low.

As pointed out above (p. 700), events of the first category undoubtedly do occur on occasion. Small amounts of "Gulf Stream" water have long been known to drift inward, toward the sector of coast line bounded on the east by Marthas Vineyard and on the west by Narragansett Bay, during most summers, bringing with them a typically tropical fauna of fishes, planktonic invertebrates, and Gulf weed (Sargassum).

Were it not for the peculiar distribution of densities off the slopes of Georges and Browns Banks, shortly to be described (p. 843), which produce more or less constant dynamic tendency for the surface stratum to move out, seaward, from the edge of the continent (a tendency altered into a long shore current to the westward by the deflective effect of the earth's rotation; p. 846), tropic water might similarly be expected to drive in over the surface right across the banks under the propulsion of high and prolonged southerly winds. Under most conditions, however, the distribution of density imposes an impassible barrier to surface drifts from the southward into the gulf (p. 939). It is fortunate for the fisheries of New England that such is the case, for were Georges and Browns Banks subject to frequent overflows by the high temperatures of the so-called "Gulf Stream" sufficient in amount to dominate the column from surface to bottom, existence on the Banks would become impossible for cod, haddock, halibut, and, in fact, for the whole category of boreal fishes.

Under exceptional conditions departures from the normal temperatures and salinities along the zone of contact of the banks and tropic waters may allow the latter to reach the Gulf of Maine as a surface drift if driven by southerly winds. An overflow of this sort was, in fact, reported by Capt. E. Kinney of the S. S. *Prince Arthur*, who observed unusually blue water with gulf weed and a temperature of 20° C. (68° F.) in the center of the gulf, latitude 42° 43′ N., longitude 69° 13′ W., on July 14, 1911, preceded for several days by a strong current toward the northwest in its western side (U. S. Hydrographic Office pilot chart for January, 1913). However, no events of this sort have come under our observation, so they must be exceptional, for their effects on the salinity of the gulf and on its plankton would be unmistakable.

It may be definitely asserted, therefore, that tropic water from outside the continental edge seldom affects the temperature or salinity of the gulf except as one of the constituents of the water that flows in through the Eastern Channel.

It is one of the most interesting oceanographic features of the Gulf of Maine that the latter is so little subject to tropic influences, either in the physical character of its waters or in its fauna or flora, when tropic water lies so close at hand.

COASTAL WATER FROM THE WEST

The possibility that the coastal water overflows around Cape Cod from the west in any considerable volume, and so into the Gulf of Maine, seems extremely remote. On the contrary, all the evidence of current-meter measurements, drift-bottle experiments, distribution of temperatures and salinities (see especially p. 974), and geographic distribution of the fauna (bottom as well as planktonic) points to just the reverse movement—i. e., out of the gulf in this side. The evidence that the dominant drift past Cape Cod, and so around or over Nantucket Shoals, is out of the Gulf of Maine, not into the latter, is conclusive.

RIVER WATER

In addition to the superficial ocean currents just discussed, which bring water to the Gulf of Maine, its tributary rivers discharge a volume of fresh water so large that it must be taken into consideration in any study of the salinity or circulation of the gulf.

Unfortunately, the annual combined discharge of the several river systems can not yet be stated, much less the contribution made by the numerous minor streams that empty into the gulf, for most of the flow measurements made by the United States Geological Survey within recent years (see especially Porter, 1899; Pressey, 1902; and Barrows, 1907 and 1907a) have been for localities far upstream. The published data for the Kennebec at Waterville, Me., and for the Merrimac at Lawrence, Mass., are perhaps the most instructive in the present connection. These records for the Kennebec cover a drainage area of 4,410 square miles[35] out of a total 6,330—i. e., about two-thirds of the river basin. The average flow is given by Porter (1899) as 6,400 cubic feet per second for the four years 1893 to 1896; and though a great number of records have been obtained subsequently, this figure may be taken as representative. In other words, if this be two-thirds of the total flow of the river (probably it is no more, because two important tributaries enter below Waterville), the Kennebec River annually pours something like 300,000,000,000 cubic feet of water into the Gulf of Maine, or enough to flood an area of about 8,000 square miles[35] to the depth of 1 foot. The discharge from the Merrimac is about the same in relation to the area of its watershed—i. e., an average of about 6,800 cubic feet per second (8 years, 1890 to 1897) from about 4,553 square miles. Flow measurements of the Androscoggin, taken at Rumford Falls, Me., at which point the river receives the run-off from one-half to two-thirds of its total watershed of 3,700 square miles, give a mean of 3,884 cubic feet per second for the years 1893 to 1901, suggesting about 6,400 for the entire watershed of this river. The discharge from the Penobscot, with its larger drainage area (8,500 square miles), averaged about 23,500 cubic feet per second for the years 1899 to 1901 (Pressey, 1902), at White Horse rips, where it drains 7,240 square miles of its total watershed of 8,500, indicating a total run-off of not less than 28,000 cubic feet per second. By a simple arithmetical calcuation the combined discharge from these four rivers alone is sufficient to raise the whole level of the Gulf of Maine, out to its southern rim, by about 1½ feet per year.

This does not include the St. John, the largest tributary of all, with a watershed more extensive than those of the Merrimac, Androscoggin, and Kennebec combined (p. 521), but for which no definite record of its discharge is available; nor of the discharges from the many lesser streams—the Saco, for example, the Presumpscot, the St. Croix, and many smaller. However, the general physical features and vegetation of northern Maine and of such parts of New Brunswick and Nova Scotia as are tributary to the gulf are comparatively uniform, as is the rainfall. Consequently, it is fair to assume that at least as large a proportion of the rain that falls on the watershed of the St. John and of the other unmeasured streams reaches the sea as from the following watersheds where this run-off has actually been measured. The run-off from the St. John watershed may, indeed, be expected to be greater, the rainfall in the interior of New Brunswick being heavier than it is over most of Maine.

River	Locality	Area of watershed, square miles	Period	Annual run-off, depth in inches, for watershed [a]		
				Maximum	Minimum	Mean
Merrimac	Lawrence, Mass.	4,452	1907-1917	24.14	13.12	17.29
Androscoggin	Rumford Falls, Me.	2,090	{1893-1902 1907-1917}	28.66	14.28	22.35
Kennebec	Waterville, Me.	4,270	1893-1916	32.45	12.73	23.08
Penobscot	West Enfield, Me.	6,600	1907-1917	32.06	14.01	25.94
St. Croix	Woodland (Spragues Falls), Me.	1,420	{1903 1907-1911}	30.52	14.96	24.14

[a] The statistics on which this and the following tables are based will be found in Porter (1899), Pressey (1902), Barrows (1907), and in U. S. Geoglogical Survey Water-Supply Papers Nos. 97, 201, 241, 261, 301, 321, 351, 381, 401, 431, 451, and 481.

The run-off from the area tributary to the St. John River may therefore be set at about 24 inches annually. Probably this applies equally to the Nova Scotian streams, while the run-off for the minor rivers along the west and north coasts of the gulf may be estimated at 18 to 22 inches—an average of not less than 18 to 24 inches for the whole watershed of the gulf.

It is not wise to estimate more precisely from data of this sort, because longer terms of observation or a multiplication of recording stations might alter the results; but the ratio that has now been established between the rainfall and the annual run-off at several observing stations confirms this calculation. Thus, Barrows (1907a, p. 110) found the run-off from the Androscoggin basin to range from 22 to 67 per cent of the rainfall over the period 1893 to 1905, averaging 59 per cent. During the same period, the run-off from the Cobbosseecontee, one of the chief tributaries of the Androscoggin, averaged 44 per cent of the rainfall (Pressey, 1902, p. 70). The average for the Presumpscott basin for 1887 to 1901 was 46 per cent of the rainfall (Pressey, 1902, p. 104), and data for the four-year period, 1914 to 1917, showed that 50 per cent of the rain that fell on the Merrimac watershed ran off via that river.

The average amount of fresh water reaching the gulf via the chief rivers tributary to it may therefore be set at about 50 per cent of the annual precipitation over its watershed, which ranges from about 38 to about 50 inches.

Assuming a yearly run-off of about 20 inches from the 61,000 square miles of watershed, this is sufficient to form a layer some 31 inches thick over the entire gulf, out to its southern rim, illustrating more concretely the relationship which this vast run-off of river water bears to the area of sea into which it is discharged. If the yearly amount by which rain and snow falling on the gulf exceeds the evaporation from its surface be something over 1 foot (p. 841), the total yearly influx of fresh water is sufficient to raise the level out to Georges Bank by at least 43 inches, or almost ⅔ of a fathom.

The seasonal distribution of this contribution of fresh water has an important bearing on the seasonal fluctuations of the salinity of the gulf (p. 701), hence demands notice here. As every New Englander knows, our rivers are in flood in spring, of which the Kennebec may serve as an illustration, both because records of its daily discharges have been kept for many years (Barrows, 1907) and because its situation and the general topography of its watershed make it typical of the rivers of Maine and New Brunswick. The following table for the 10-year period, 1893 to 1902, is compiled from Barrow's (1907) records.

Mean discharge of Kennebec River at Waterville, Me.

Month	Run-off, cubic feet per second	Run-off, in inches	Month	Run-off, cubic feet per second	Run-off, in inches
January	2,919	0.76	August	3,811	1.03
February	3,357	.82	September	2,893	.75
March	8,454	2.28	October	3,011	.82
April	24,811	6.49	November	4,685	1.23
May	20,032	5.40	December	3,944	1.17
June	10,031	2.62			
July	6,116	1.65	Monthly mean	7,838	2.10

Two-thirds of the total run-off for the year thus falls during the three spring months, and more than half of it during April and May. This does not exactly represent the natural condition, because the Kennebec is more or less controlled by the several dams; but water-power developments have not been sufficient to mask its spring freshets—still less have they on the Penobscot or the St. John Rivers. Hence, the seasonal fluctuations in the flow of the Kennebec may be taken as generally representative of all the considerable streams that empty into the gulf north and east of Cape Elizabeth and of the Saco as well.

Originally the Merrimac, also, came into flood in the spring, at the season when the snow blanket melts and the ice goes out; but it is now so largely harnessed for industrial purposes that its seasonal flow no longer shows as pronounced a freshet in April and May as New England waterways do in their natural state. Its largest run-off still falls in April, however, and its smallest in September, as appears from the following table:

Merrimac River at Lawrence, Mass., for the period 1907 to 1916

Month	Run-off, in inches	Month	Run-off, in inches
January	1.3	August	0.8
February	1.2	September	.6
March	2.7	October	.8
April	3.6	November	1.0
May	2.3	December	1.1
June	1.3		
July	.8	Monthly average	1.4

Automatic tide gauges, which have been in operation at a number of points around the coastline of the gulf between Cape Cod and the Bay of Fundy, have shown the sea 0.1 to 0.2 feet lower than the mean in the latter part of winter, and about this same amount higher than the mean toward the end of the summer.[36] This variation probably reflects the seasonal variation in the inflow of land water.

RAINFALL AND EVAPORATION

Although land drainage is the chief source for fresh water for the gulf, rainfall also adds a considerable increment. No record of the precipitation over the offshore parts of the gulf itself is available, but the monthly and annual averages for four representative coast stations—Boston, Portland, Eastport, and Yarmouth—tabulated below suggest an annual fall of 40 to 45 inches for the gulf as a whole.

Average rainfall, in inches

Month	Boston	Portland	Eastport	Yarmouth	Month	Boston	Portland	Eastport	Yarmouth
January	3.82	3.81	3.84	5.16	August	4.03	3.57	3.26	3.62
February	3.44	3.65	3.62	4.17	September	3.19	3.20	2.97	3.61
March	4.08	3.75	4.28	5.00	October	3.86	3.66	3.85	4.12
April	3.60	3.11	2.94	3.82	November	4.10	3.80	4.08	4.49
May	3.55	3.67	3.80	3.57	December	3.41	3.68	3.97	4.77
June	3.03	3.36	3.24	2.93					
July	3.36	3.25	3.42	3.47	Total	43.40	42.50	43.30	48.73

[36] Information contributed by U. S. Coast and Geodetic Survey.

Evaporation, of course, partially offsets precipitation. Unfortunately, no data are available on this subject from any localities that might be supposed to approximate conditions as they prevail at sea in the Gulf of Maine; the outer islands, for example, would be such. Nevertheless, there is no reason to suppose that evaporation at sea is greater than on land, especially when the sea is blanketed with thick fog, as the northern and northeastern parts of the gulf and its offshore banks often are during the summer season. The following records of evaporation for Maine, Massachusetts, and Nova Scotia may therefore be taken as the maximum. The average monthly evaporation from a free water surface at three stations in Maine in the basins of the Penobscot, Kennebec, and Androscoggin Rivers is given by Barrows (1907a, p. 114) as follows, in inches:

Month	Average evaporation, in inches	Month	Average evaporation, in inches
March	2.23	July	5.28
April	3.48	August	5.12
May	1.90	September	3.00
June	2.87	October	2.33

No data are available for the winter months, when the observations were necessarily made from a frozen surface, but it may be assumed that evaporation takes place no more rapidly from open water from November through February than in October or March—say at the rate of about 2.2 inches monthly. This suggests a total evaporation for the year of about 35 inches of fresh water.[37] According to Fitz-Gerald (1886), the annual evaporation is somewhat larger near Boston (about 39 inches), as might be expected.

Data supplied by the United States Weather Bureau for Yarmouth, Nova Scotia, more closely paralleling conditions over the gulf because of the greater frequence there of onshore winds, show the following monthly averages over a period of 13 years:

Evaporation at Yarmouth, Nova Scotia

Month	Average evaporation, in inches	Month	Average evaporation, in inches
April[1]	1.08	August	3.55
May	3.04	September	3.57
June	3.49	October	1.59
July	3.94		

[1] 1920 only; ice in the tank on several days.

Assuming an average evaporation of 1.5 to 2 inches monthly, for the period November to March, the annual evaporation of fresh water at Yarmouth would be close to 29 inches from a surface of open (not frozen) water; the average for the Gulf of Maine is probably not more than 30 inches. These measurements are for fresh

[37] These measurements were taken freely exposed to the sky (Barrows, 1907a, p. 114, pl. 21).

water, however, which evaporates somewhat more rapidly than salt water under equal conditions of temperature, humidity, etc. According to Mazelle (1898), the evaporation of salt water averages about 81 per cent that of fresh at Trieste, while Okada (1903) found it averaging about 95 per cent that of fresh over a 7-year period in Japan. As Okada's measurements were taken open to the sky, Mazelle's under a roof, the former simulate more the conditions at sea.[38]

As a rough approximation, the evaporation of salt water from the surface of the Gulf of Maine may, then, be set at about 27 to 28 inches, or about 71 centimeters, annually.

DEEP STRATUM

SLOPE WATER

The scources so far mentioned contribute chiefly to the superficial stratum of the Gulf of Maine. We must next consider the comparatively warm and highly saline water that drifts intermittently inward along the trough of the Eastern Channel to form the bottom water of the gulf. The high salinity of this makes its offshore origin clear enough. As certainly, however, it is *not* a direct and unmixed indraft from the mid depths of the Atlantic Basin. Two reasons warrant this confident assertion. In the first place, neither the temperature nor the salinity of the bottom water of the Eastern Channel, or of the gulf basin within, is high enough to accord with such an origin. In the second place, profiles enough have now been run by various expeditions to make it certain that a broad band, intermediate in temperature and in salinity between the coastal water, on the one hand, and the tropic Atlantic water, on the other, always separates the latter from the edge of the continent from Georges Bank to the Grand Banks.

The "cold wall" of the earlier oceanographers—the source of this band—has been the subject of much discussion, with upwelling from the ocean abyss and currents from the north most freqently invoked to explain its low temperature as contrasted with the "Gulf Stream" on its seaward side. Recent explorations, however, have made it clear that this "cold wall" is simply the product of the mixture that is constantly taking place between the tropic water, on the one hand, and the coastal water, on the other (or Arctic water in the Grand Banks region), at their zone of contact along the slope of the continent. "Slope water," as defined by Huntsman (1924), is therefore a better name for it than "cold wall," and as such it is referred to repeatedly in the preceding pages.

It is the presence of a continuous zone of this slope water right across the mouth of the gulf at all times of year which effectively bars unadulterated oceanic or tropic water from entering the Eastern Channel. It is because the most saline bottom water of the gulf draws from this source that members of the bathypelagic plankton of the Atlantic Basin occur only as the rarest of stragglers within the gulf (Bigelow, 1926, p. 67).

Explorations by the Canadian Fisheries Expedition (Bjerkan, 1919; Sandström, 1919; and Huntsman, 1924) have similarly proven that the high salinity (34.5 to 34.7 per mille) and comparatively high temperature (4° to 5°) of the deepest stratum

[38] For further discussion of evaporation see Krümmel, 1907, p. 244.

of the Gulf of St. Lawrence are similarly maintained by an inflowing bottom current of the same slope origin.

The motive power that brings water of this character to the Gulf of Maine as a bottom current through the Eastern Channel (intermittently, it is true, but regularly enough to maintain the comparatively constant salinity and temperature actually recorded) is to be sought in the distribution of density along the edge of the continent. A considerable body of evidence has now been accumulated to the effect that the zone of contact along which coast and ocean waters mix, and where the slope water is manufactured, averages somewhat more dense (heavier) than the water in on the edge of the continent, except right at the surface. All the profiles that have been run out across the continental edge off Nova Scotia in summer, both those by the Canadian Fisheries Expedition (Sandström, 1919, pl. 9, sections 13, 14, 15, 16, and 17) and by the United States Bureau of Fisheries, have shown something of this sort. Thus, on July 25 to 28, 1914, on the first *Grampus* profile out from Shelburne (stations 10231, 10232, and 10233), the stratum between the 20-meter and 150-meter levels was more dense just outside the edge of the shelf than in over the latter, though the surface was less so.

The *Grampus* again found the water heavier over the continental slope (station 10295) than in over the shelf (fig. 168) along this same profile on June 23 and 24, 1915, with a decidedly steep density gradient at the 50 to 100 meter level. Consequently, the whole mass of water on the shelf above 100 meters must have had a hydrostatic tendency to drift seaward, except immediately at the surface.

A March profile along this same general line (stations 20073 to 20077) again shows higher densities at the outermost station, at 100 to 220 meters, than along the edge of the continent (fig. 169)—evidence of this same dynamic tendency for the water of low salinity and temperature to move out across the slope, though at the inshore end of the profile the dynamic tendency in the superficial stratum was the reverse.

The water at 20 to 120 meters' depth was likewise somewhat more dense over the southeastern slope of Georges Bank (station 10220) than in on the neighboring edge of the latter (stations 10221 and 10225) in July, 1914; again in April, 1920 (stations 20109 to 20111), though our corresponding profile for March, 1920, crossed a more complex alternative of heavier and lighter bands there (stations 20065 to 20069).

The cross section of the western end of Georges Bank for July 20 and 21, 1914 (fig. 170), is especially instructive in this connection, being the only one of our profiles that has reached water of oceanic salinity (36 per mille). Here, again, the upper 50 meters of water proved slightly more dense at the outer end (station 10218) than over the neighboring edge of the bank (station 10216), resulting in a comparatively steep south-north gradient of density, though the relationship was just the reverse at a depth of 70 to 140 meters. A slight differential of this same order (density higher at the outermost stations than in on the bank) also prevailed in this same general region in February and again in May of 1920 (stations 20045 and 20046 for February; 20128 and 20129 for May); but in the cold July of 1916 this seems to have applied only at depths greater than

40 meters, with the surface water more dense over the bank (station 10348) than over its seaward slope (stations 10349 and 10352), though some doubt exists as to the salinity (hence as to the density) at the critical station (10349, p. 992).

Thus, densities rule lower along the outer edge of the offshore banks, abreast of the Gulf of Maine and off Nova Scotia to the eastward, than along the continental slope that bounds the banks on the offshore side. The relationship at any given date may be of the reverse order, either close to the surface as in July, 1916, or

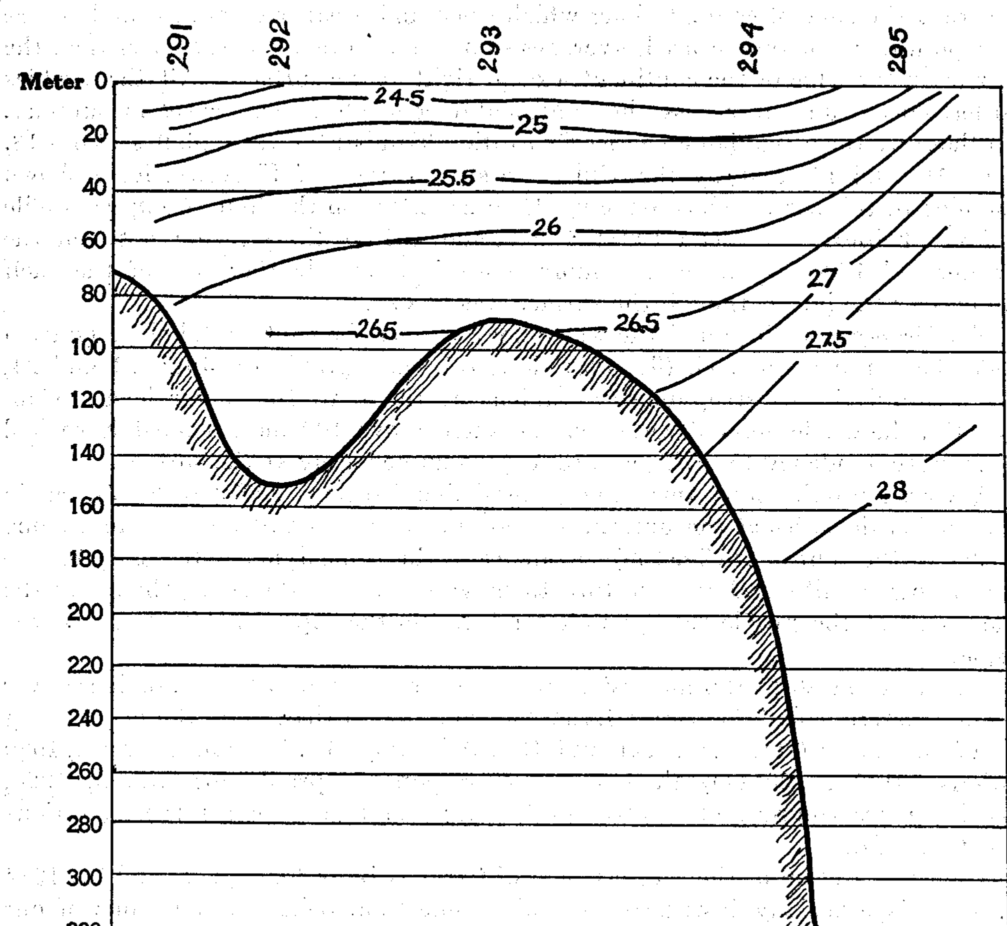

FIG. 168.—Density profile crossing the continental shelf in the offing of Shelburne, Nova Scotia, June 23 to 24, 1915. Corrected for compression

along the 100-meter contour, as in July, 1914. However, we have never failed to find the surfaces of equal density rising comparatively steeply from the outer part of the shelf through the greater part of the depth zone there included, out across the edge of the continent between the longitudes of Shelburne, Nova Scotia, and of Cape Cod.

To the east and north of our limits, and especially off the Newfoundland Banks, this zone of mixture is not only heavier than the coast water on its inner side (or

Arctic water, according to locality), but often, if not always, heavier than the tropic water on the outer side as well (Witte, 1910; E. H. Smith, 1924, p. 140, 1925, figs. 10, 12, and 19), causing the dynamic tendency for surface water to move in from both sides toward this heavy zone (or "cabelling"), which seems first to have been emphasized by Witte (1910). Huntsman, too (1924, p. 278), definitely accepts "cabelling" as a governing event in the formation of the slope water; and although more recent hydrodynamic studies (see especially E. H. Smith, 1926) have made it clear that actual sinking is usually prevented there by the effect of the earth's rotation, a potential

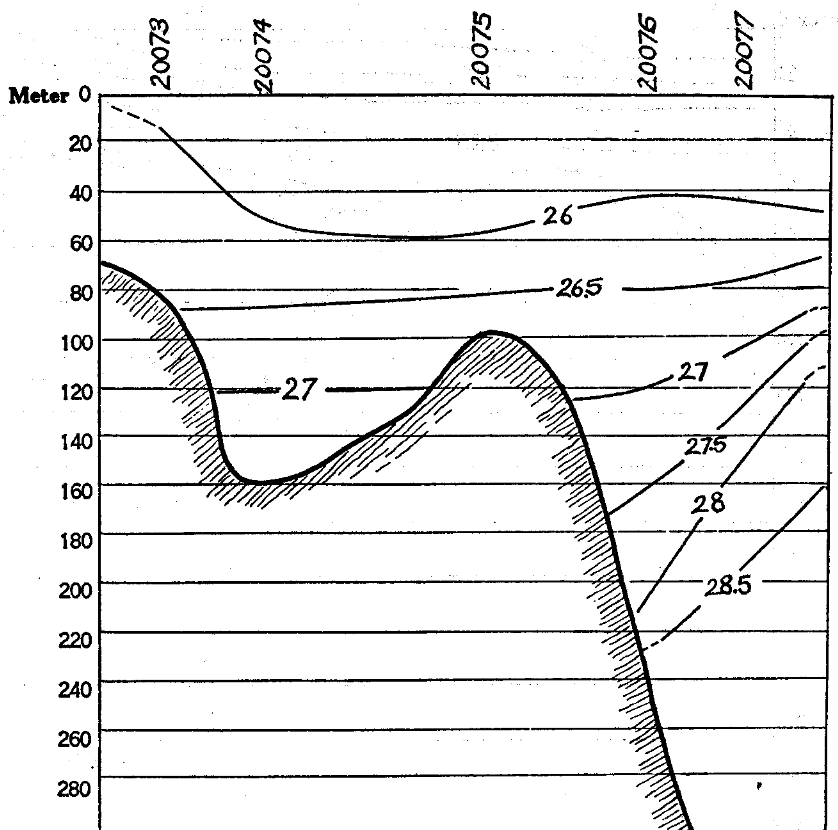

FIG. 169.—Density profile crossing the continental shelf in the offing of Shelburne, Nova Scotia, March 17 to 20, 1920. Corrected for compression

sinking zone of this sort does nevertheless tend to draw in surface water from both sides toward the zone where the surfaces of equal density depart most from the horizontal, and so to set up a horizontal circulation.

A potential sinking zone of this same sort was revealed by one profile run off La Have Bank by the Canadian Fisheries Expedition in July, 1915, when the upper 100 meters proved more dense just outside the edge of the continent (Bjerkan, 1919, *Acadia* stations 41 to 43) than in on the edge of the shelf, on the one hand (*Acadia* stations 39 and 40), or at the outermost station, on the other (*Acadia* station 44).[39] It is doubtful how regularly profiles abreast of the gulf or off southern New England would show this decrease in density seaward from the continental slope.

In the preceding discussion I have taken pains to speak always of a "dynamic tendency" toward movements of the water, never of such movements as taking place; because in our latitudes the currents that actually follow inequalities of density of this sort are given quite different characters by the deflection resulting from the

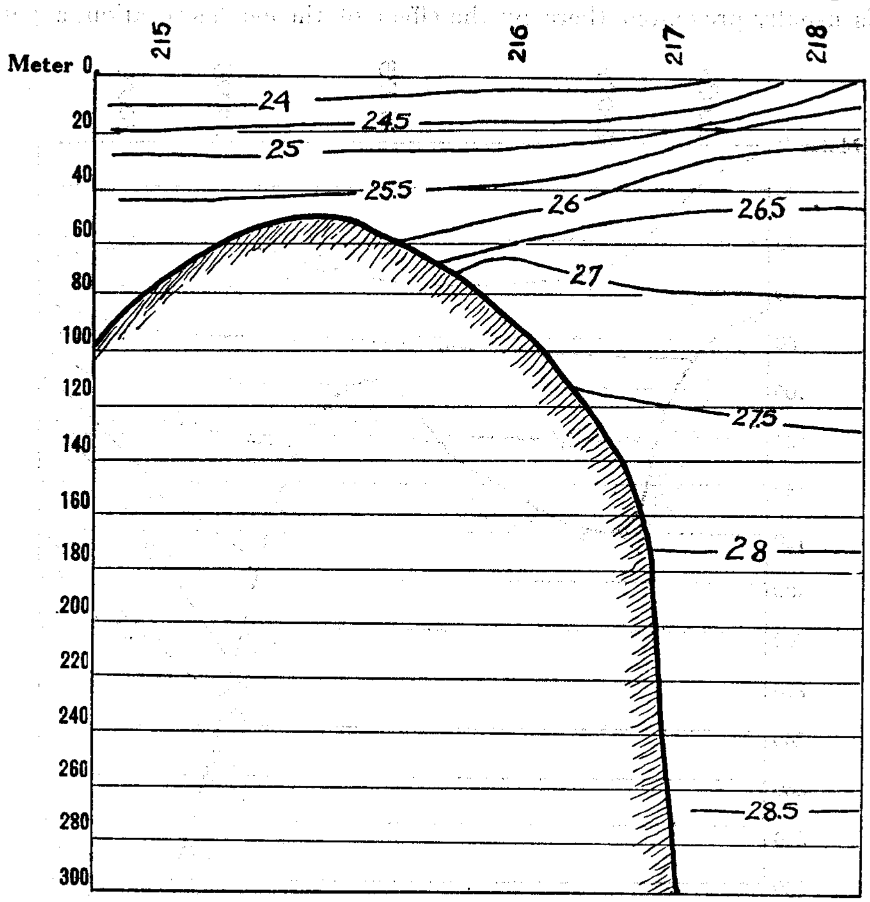

FIG. 170.—Density along a cross profile of the western part of Georges Bank, July 20 and 21, 1914 (stations 10215 to 10218). Corrected for compression

rotation of the earth, by which the apparent track of any current (or other body moving freely over the earth) in the Northern Hemisphere is deflected to the right.[40]

The rôle that this quasi-force plays in directing the ocean currents, however set in motion, is now so generally appreciated that no discussion of it is called for here.

[39] None of our *Grampus* or *Albatross* profiles have run out far enough to show this relationship, if it existed.

[40] Krümmel (1911, p. 449) and Sandström (1919) have given perhaps the simplest statements of this subject, in its oceanographic bearing, and discussions of the effects of the centrifugal force resulting from the earth's rotation in relation to the ellipsoid form of the earth. See also Ferrell (1911), Davis (1885 and 1904), and Bjerknes (1910 and 1911).

Baldly stated, its practical effect on the slope water which dynamic forces tend to drive out to sea from the continental slope, as described above (p. 843), is to swing this drift to the right (i. e., to the west), thus altering into a longshore current what otherwise would be (and potentially is) an offshore set.[41]

In this way a dominant drift from east to west tends to develop along the upper part of the continental slope of La Have and Browns Banks so long as the distribution of density is of the type actually recorded on the *Acadia*, *Albatross*, and *Grampus* cross profiles of this part of the continental shelf for March, 1920, June and July, 1915, and July, 1914. On each of these occasions the dynamic tendency, acting as the propulsion for such a drift, involved the whole mass of bottom water from the crest of La Have Bank down the slope to a depth of at least 200, if not 250, meters. An east-west drift of the bottom water seems, then, comparatively constant on just this part of the slope.

In July, 1915, this drift involved the whole column of water, surface to bottom; again, in July, 1922, when bottles set out near the edge of the shelf in the offing of Cape Sable drifted into the Gulf of Maine (p. 908). Sandström's (1919) calculation of a surface current of about 5 miles per day[42] toward the southwest, along the outer part of the shelf, on this line (between *Acadia* stations 39 and 41), shows that the surface water may travel with considerable velocity at times when the whole column is involved in this westerly set along the edge of the continent. This is confirmed by the drifts of four bottles set out 48 to 60 miles off Cape Sable in July, 1922, three of which went to the Bay of Fundy at minimum rates of 3 to 4 miles per day, and one to Winter Harbor, near Mount Desert, at a daily rate of at least 2 miles, and probably considerably faster than that (p. 908). However, the obliquity of the surfaces of equal density, which originates this drift, decreased with increasing depth on the *Acadia* section, so that Sandström's (1919, p. 332) table indicates a mean velocity of only about 1 mile per day for the whole column of water, surface to bottom, between the critical stations (from No. 40 out to the 200-meter contour), with the bottom water creeping westward not faster than about one-half mile per day[43] at a depth of 100 to 200 meters.

The outermost bottle (which is known to have gone to the Gulf of Maine from the line put out off Cape Sable by the Biological Board of Canada in 1922) was set adrift over the 200-meter contour[44] 59 miles out from the land, the only returns from bottles set adrift farther out coming from Europe. This limitation of the westerly drift to a narrow belt corroborates the *Acadia* profile of July, 1915, on which it was only about 20 miles wide (and similarly located), giving place farther out to a succession of lighter and heavier bands, indicating a stronger but even narrower countercurrent to the eastward; then, outside of that, a second line of drift to the westward.[45]

Evidently an active mixing of cold and warm waters was taking place at the outer end of this profile at the time, with bands of higher and lower temperature

---

[41] See Smith's (1926) exposition of this important concept.

[42] The velocity arrived at by Sandström (1919) from hydrodynamic calculation are only *relative* to the most nearly stationary stratum of water, not absolute. This does not lessen their significance in the present case, for with the whole column moving in the same direction the actual velocities would be somewhat greater than the calculated.

[43] About 1.4 centimeters per second, or 0.025 knot per hour.

[44] Information contributed by Doctor Huntsman.

[45] See Sandström (1919, pl. 15) for the calculated velocities of these two lines of drift.

eddying in the extremely complex fashion that may be expected to characterize the zone of contact between waters that differ widely in their physical character and in their direction of flow.

Similar alternations between colder (and less saline) and warmer (and more saline) bands have been reported on several occasions and at localities widely separated off the eastern seaboard of North America; but in most cases, at any rate, these are transitory and rapidly changing phenomena. The westward drift of water close in to the upper part of the slope, just described, has, on the contrary, proved characteristic of the La Have Bank region; and so long as the dynamic motive for this drift persists, the neighboring oceanic triangle off the mouth of the Eastern Channel is supplied with slope water from the eastward. By this reasoning, the current that flows into the bottom of the gulf via the Eastern Channel draws from the slope water manufactured at about an equal depth on the Nova Scotian slope—chiefly between Browns and La Have Banks—not from shoaler or deeper strata there.

This conclusion is confirmed by the fact that temperature and salinity proved very nearly the same on bottom in the channel (34.7 to 35 per mille and 6° to 7° at 200 to 250 meters) as at equal depths on the slope between these two banks (34.6 to 34.9 per mille and about 7° to 8°) in July, 1914, in June, 1915, and again in the spring of 1920.[46]

Further evidence that the indraft into the channel is supplied from the eastward, not from the westward, is afforded by the fact that considerably lower temperatures and salinities have been recorded around the eastern and southeastern slopes of Georges Bank (p. 714). In fact, there is reason to believe that the western side of the channel is the site of a dominant drift outward from the gulf (p. 974).

The cold band encountered off the southwest slope of Georges Bank by the *Grampus* in July, 1916, and reported there in other summers (pp. 608, 919) may also be credited with an eastern source, because its temperature and its salinity both agree closely with that of the slope water that is manufactured in the offing of Cape Sable in early summer, as exemplified by the observations taken there in June, 1915, and July, 1914 (p. 629; Bigelow, 1922, p. 166). Thus it owes its low temperature indirectly to the Nova Scotian current (and so to ice melting far to the eastward).

Why this southwesterly cold current was so much more in evidence along the bank in 1916 than in 1889, 1913, or 1914 remains an open question, but it seems probable that some westerly movement of slope water takes place along Georges Bank to a greater or less extent every spring as the Nova Scotian current floods to its maximum velocity and volume. In some years (1889, for instance, and 1916) this drift persists into the summer, as seems to have been the state in 1922, also, when so many of the bottles set out at the edge of the continental shelf in July made long drifts to the westward (p. 882). In other years (exemplified by 1914) it seems to be obliterated west of longitude about 68° by July, as the tropic water advances toward the edge of the continent. But although so variable, the existence of this cool band in some summers is extremely instructive as one of the several

[46] The slope water was somewhat more saline at this locality at the end of July, 1915 (Bjerkan, 1919, *Acadia* station 41), but no observations were taken in the channel at the time.

evidences of the general tendency of the slope water to move westward from the Nova Scotian slope.

The slope water, moving westward, is forced against Browns Bank by the earth's rotation. Consequently, with the Eastern Channel offering an open route for it to the right, it is reasonable to think of a screwing motion as taking place into the latter around the southerly and southwesterly slopes of Browns Bank so long as the propulsive dynamic force resulting from regional inequalities of density persists over the Nova Scotian slope to the eastward.

Additional evidence that the bottom water does actually move inward through the Eastern Channel is afforded by the inequalities of density within the basin of the gulf, where the surfaces of equal density (approximately horizontal in the upper 50 to 60 meters) show a considerable slope from the channel inward at depths greater than 80 to 100 meters.

This density gradient in the deep water may be illustrated most graphically by charting the depth to which it is necessary to sink in order to reach water of a given value, choosing 1.027 as the most illustrative (figs. 171 and 172). The precise upper contour of this mass of heavy bottom water has varied from month to month, as might be expected. Thus, in June, 1915, the slope was steepest near the entrance to the channel, with the surfaces of equal density lying nearly horizontal thence inward along the western arm of the basin. In July and August of 1914 the the most abrupt slope, involving the whole column of water deeper than 50 meters (fig. 171), was situated farther within the basin. A density gradient of the same sort was again recorded in the eastern part of the basin in March, 1920, and a weaker contrast (but one of the same order) between the channel, on the one hand, and the inner parts of the basin, on the other, in April of that year, sufficient to show it a permanent characteristic of the gulf.

The implication of a density gradient of this sort is obvious. Only by the introduction of heavy water into the gulf via the channel could it be maintained against the action of the hydrostatic forces that are constantly tending to make horizontal the surfaces of equal density.

The inflowing bottom current, which maintains the high salinity (34.5 to 35 per mille) of the deeps of the gulf, thus corresponds, both in cause and in effect, to the indraft of offshore water that has been recorded in many an estuary. The gulf, in fact, is nearly as estuarine in this respect as it would be if the offshore banks (Georges and Browns) were above water, and so actually inclosed it except for the deep channels between.

In the preceeding discussion I have spoken as though this inflowing current and the gradients of density that give rise to it were comparatively constant. Actually, however, our observations on temperatures and salinity have revealed considerable fluctuations in the volume of water that enters the gulf via this route at various seasons and in various years.

It goes almost without saying that no sharp distinction can be drawn in salinity between waters of different origins, especially where the water is stirred as actively as it is in the Gulf of Maine; but the isohaline for 34 per mille may be taken as roughly outlining the "slope water" that has recently entered the gulf or that has continued little altered during its sojourn there, if the product of an earlier invasion.

So far as our records go, slope water of this high salinity reaches its widest expansion within the gulf in April (p. 737). The indraft through the channel, however, seems to slacken during that month, for the bottom layer of 34 per mille water was

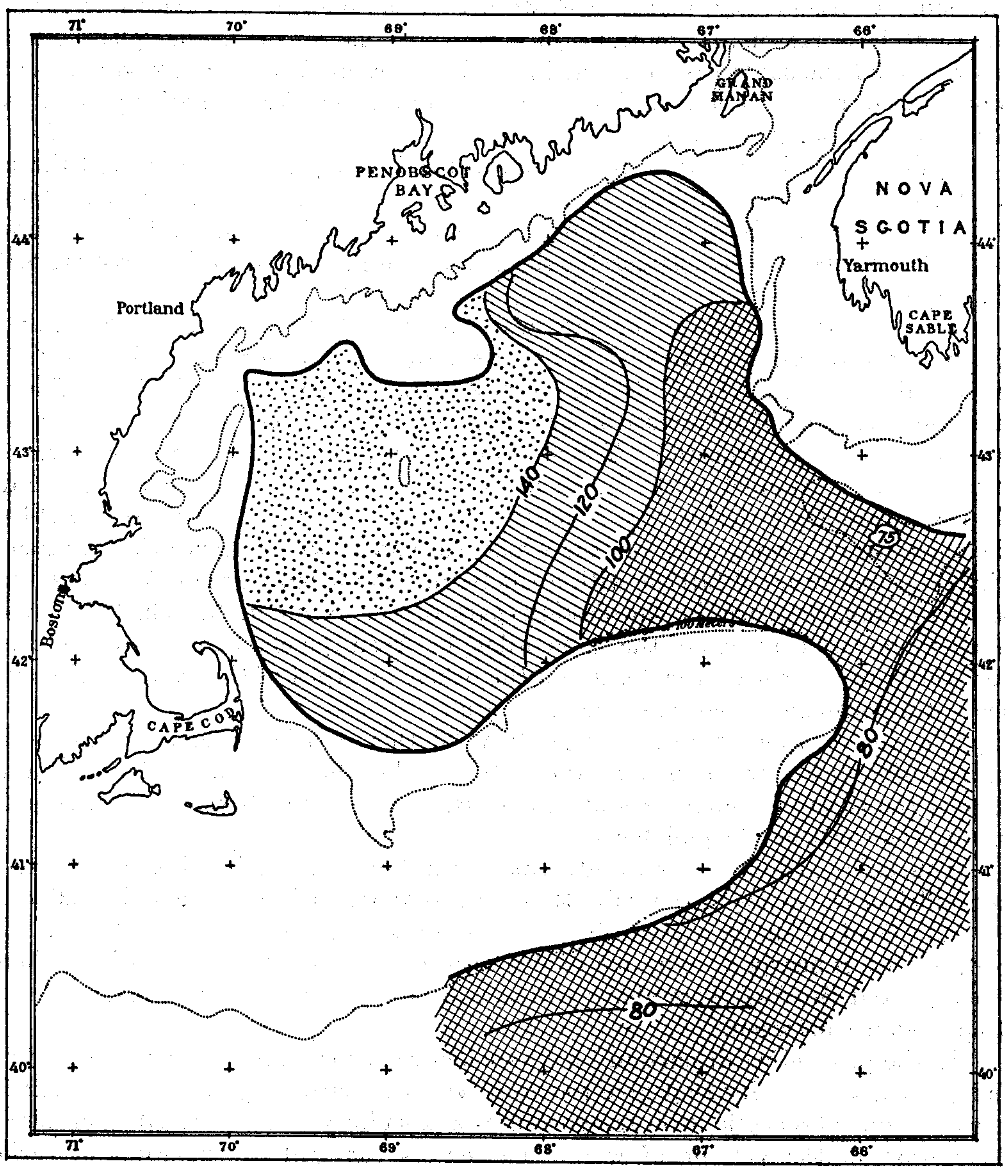

FIG. 171.—Depth of the density surface (isopycnobath) for 1.027; July and August, 1914. Corrected for compression

much thinner in May [47] of 1915 than in March or April of 1920 (p. 754), and the area occupied by it was much less extensive. In that year (probably a representative one) but little water can have moved inward through the Eastern Channel during

[47] In May, 1915, the bottom water of the western arm of the basin was more saline than 34 per mille; that of the eastern less so